

Comparison of Penetration Efficiency in Axial and Planer Symmetries

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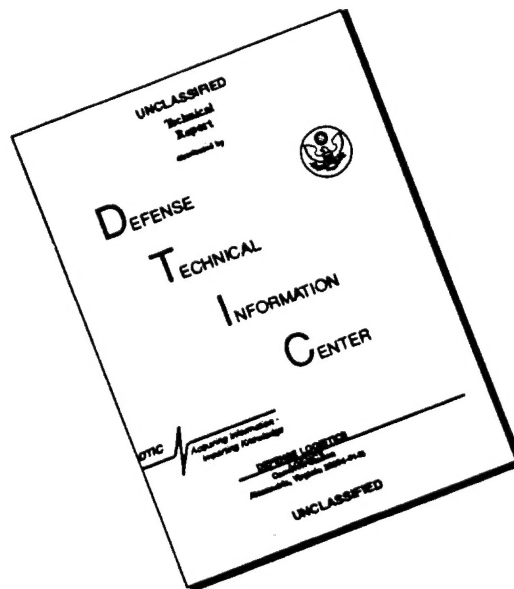
November 1993

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| 13. ABSTRACT (Maximum 200 words) It has been known for some time that, for a given target, a flat cross section projectile would penetrate deeper than a circular cross section projectile, other factors being equal. This invoked the idea that a cruciform cross section projectile would have an advantage over the circular cross section projectile. We used AUTODYN2D to simulate penetration of steel and tungsten alloy projectiles into steel targets for axial and planar symmetries. The purpose was to see to what extent the planar projectiles have an advantage over circular projectiles. We found that: planar projectiles penetrate more than circular projectiles at low velocities (1.5 km/s); planar projectiles lose their advantage with increasing velocity; much larger target dimensions are needed for full confinement of planar projectiles; and craters created by planar projectiles are much wider and their width is not constant. | | | |
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Comparison of Penetration Efficiency in Axial and Planer Symmetries

by
Yehuda Partom

It has been known for some time that, for a given target, a flat cross section projectile would penetrate deeper than a circular cross section projectile, other factors being equal. This invoked the idea that a cruciform cross section projectile would have an advantage over the circular cross section projectile.

To simulate the penetration process of a cruciform projectile, we need to employ a 3D wavecode. As such a code is not yet available to us, we conducted a preparatory investigation using the 2D wavecode AUTODYN2D. We ran identical penetration problems in axial and planar (2D strain) symmetries. The planar symmetry projectile can be regarded as an extreme case of a flat projectile. This means that if indeed a flat projectile is more efficient than a circular projectile, the flat projectile (being laterally finite) always penetrates less than the equivalent planar symmetry projectile. Therefore, the basic idea of the investigation is as follows. If the simulations show that a planar symmetry projectile has sufficient advantage over the equivalent axial symmetry projectile, then a cruciform projectile may be a promising design.

In all simulations we used a steel target and steel or tungsten alloy $L/D = 10$ projectiles. We used a Mie-Gruneisen EOS referenced to the shock adiabat with the parameters listed in Table 1 below:

Table 1
EOS Parameters

| | Steel | Tungsten Alloy |
|------------|------------------|----------------|
| ρ_0 | 7.85 g/cc | 17.3 g/cc |
| C_0 | 3.57 mm/ μ s | 4.03 |
| S | 1.92 | 1.24 |
| Γ_0 | 1.7 | 1.7 |
| P_{min} | -2 GPa | -2 GPa |

where ρ = density, C_0 , S are the shock velocity particle velocity relation parameters, Γ_0 = Gruneisen parameter and P_{min} is the spall strength.

For the stress deviator we used a constant shear modulus G and a von Mises yield surface with a constant flow stress Y as shown in Table 2:

Table 2
Shear Stress Parameters

| | Steel | Tungsten Alloy |
|-----|--------|----------------|
| G | 80 GPa | 140 GPa |
| Y | 1 GPa | 2 GPa |

Projectile dimensions were $D/2 = 5$ mm, $L = 100$ mm; the Euler cell dimensions were 1×1 mm. Target dimensions varied according to symmetry, projectile material (steel or Tungsten alloy) and velocity. Specifically, in the planar symmetry case, we observed that very large target dimensions are needed to exert a reasonable amount of confinement. Target dimensions used in the various cases are listed in Table 3.

Table 3
Target Dimensions

| No. | Projectile Material | Symmetry | Velocity (km/s) | $D_t/2$ (mm) | L_t (mm) |
|-----|---------------------|----------|-----------------|--------------|------------|
| 1 | Steel | Circular | 1.5 | 100 | 100 |
| 2 | " | " | 2.0 | 100 | 200 |
| 3 | " | " | 2.5 | 100 | 200 |
| 4 | " | planar | 1.5 | 250 | 250 |
| 5 | " | " | 2.0 | 280 | 280 |
| 6 | " | " | 2.5 | 280 | 280 |
| 7 | tungsten alloy | circular | 1.5 | 100 | 150 |
| 8 | " | planar | 1.5 | 280 | 280 |

In the axial symmetry runs, cell dimensions in the target were also 1×1 mm. In the planar symmetry runs, cell dimensions were 1×1 mm for $x < 100$ mm and $y < 100$ mm, where $x = 0$ is the impact surface and $y = 0$ is the (planar) symmetry axis. Beyond $x = 100$ mm and

$y = 100$ mm, cell dimensions grew progressively. There were 8 runs as shown in Table 3. The initial plan included 6 runs: 2 projectile materials (steel and tungsten alloy), 2 velocities (1.5 and 2.5 km/s (only for the steel projectile), and 2 symmetries (axial and planar); however, the higher velocity runs provided an unexpected result. To convince ourselves that there was no error, we did 2 additional runs with the steel projectile at an intermediate velocity (2 km/s). To document the runs we show plots of material status and velocity vectors (near the projectile target interface) in Appendix A (included only in 2 copies of this report). The plots are snapshots every 200 cycles. They are arranged according to the run numbers in Table 3. To analyze the results of these runs, we show interface velocity and projectile tail velocity history plots and penetration-erosion curves.

The velocity plots are shown in Figs. 1.1 to 1.4.

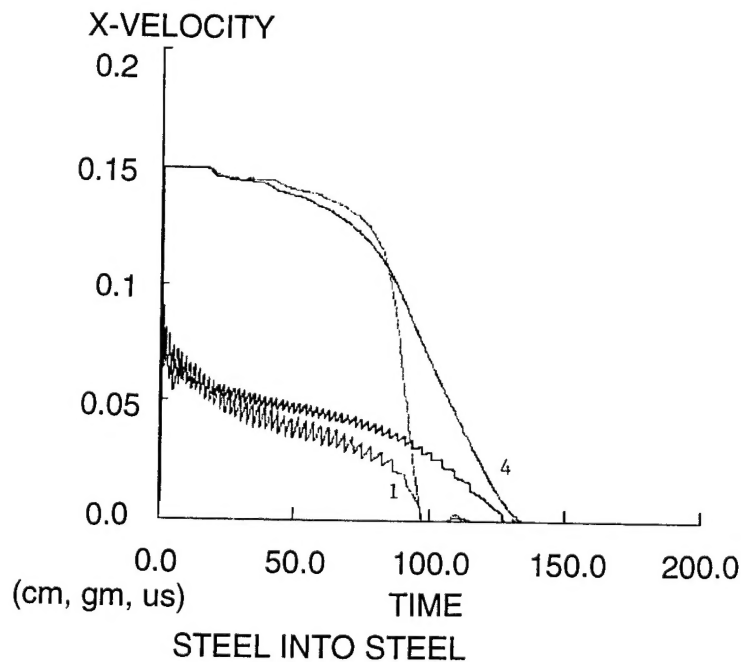


Fig. 1.1. Runs 1 and 4.

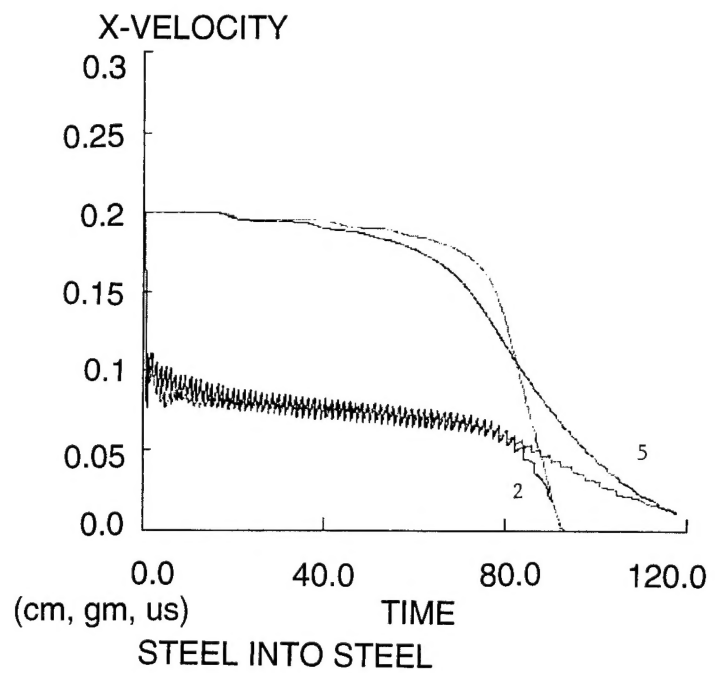


Fig. 1.2. Runs 2 and 5.

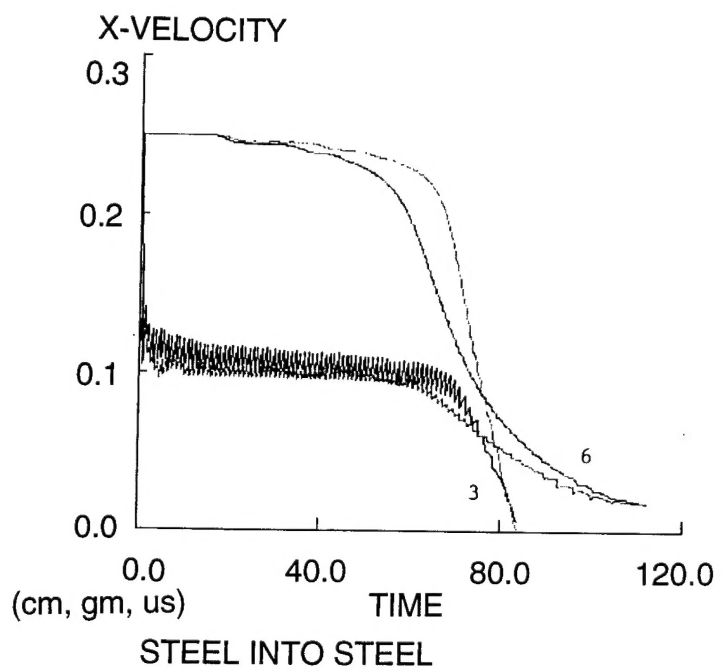


Fig. 1.3. Runs 3 and 6.

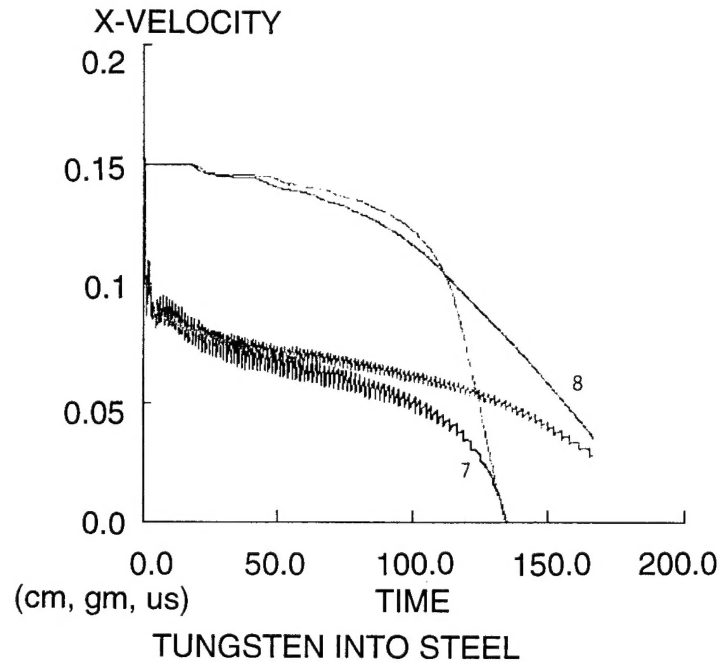


Fig. 1.4. Runs 7 and 8.

Figure 1.1 to 1.4 Interface velocity and projectile tail velocity histories (1.1 is for runs 1 and 1.2 is for runs 2 and 5, 1.3 is for runs 3 and 6, and 1.4 is for runs 7 and 8).

Figs. 1.1 and 1.4 are for $V = 1.5$ km/s for steel into steel and for tungsten alloy into steel respectively. In both figures, we see that the penetration velocity for planar symmetry is high. This is not the case for $V = 2$ km/s and $V = 2.5$ km/s. In Fig. 1.2 ($V = 2$ km/s, steel into steel), we see that the penetration velocities for planar and axial symmetries are about equal. In Fig. 1.3 ($V = 2.5$ km/s, steel into steel), we see that the penetration velocity for planar symmetry is high than that for axial symmetry. This shows that a planar symmetry projectile has an advantage at low velocities but loses its advantage with increasing velocity. We see this behavior even more clearly in the penetration-erosion curves shown in Figs. 2.1 to 2.4.

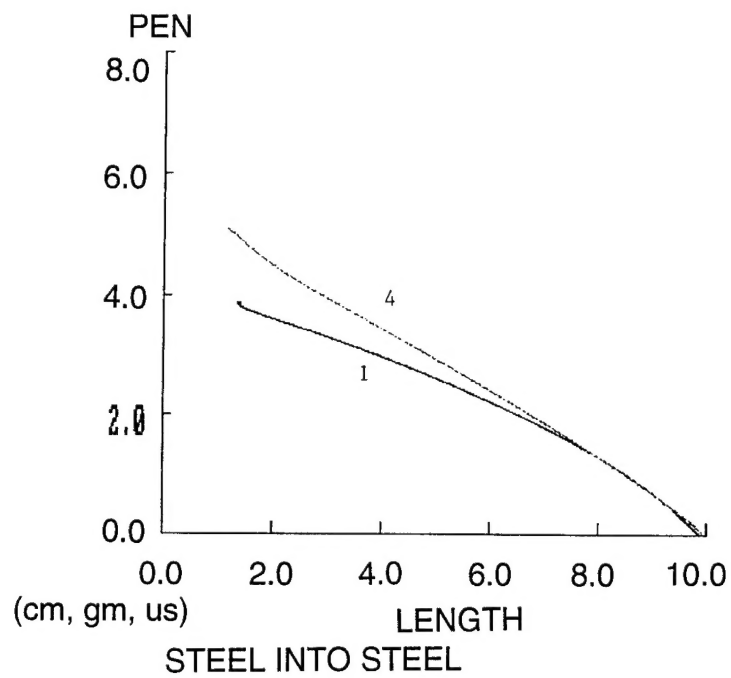


Fig. 2.1. Runs 1 and 4.

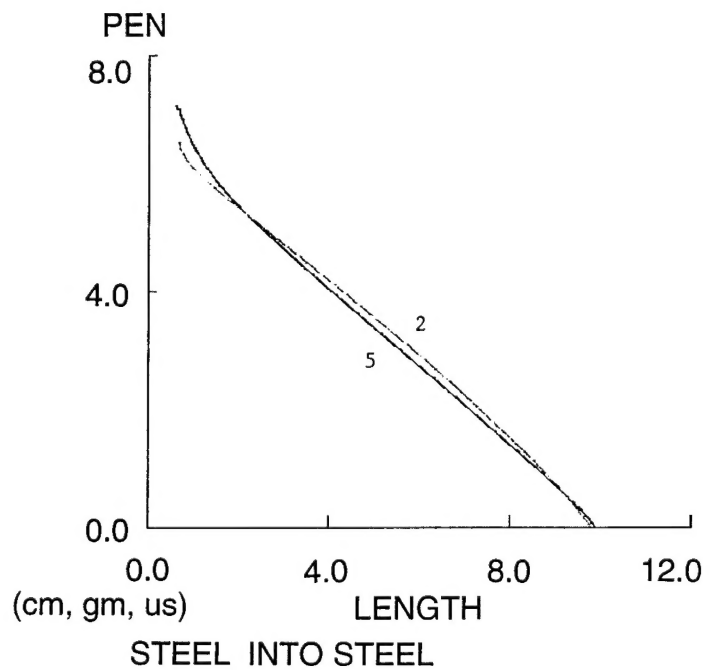


Fig. 2.2. Runs 2 and 5.

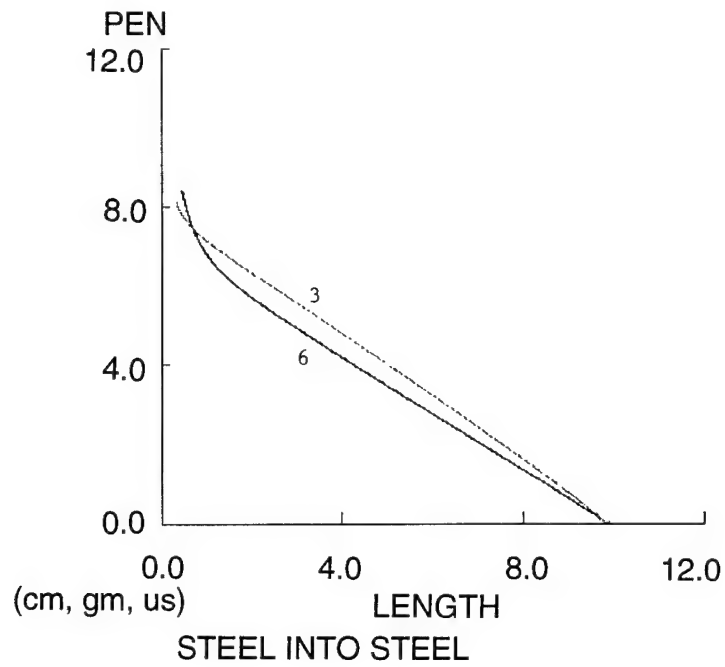


Fig. 2.3. Runs 3 and 6.

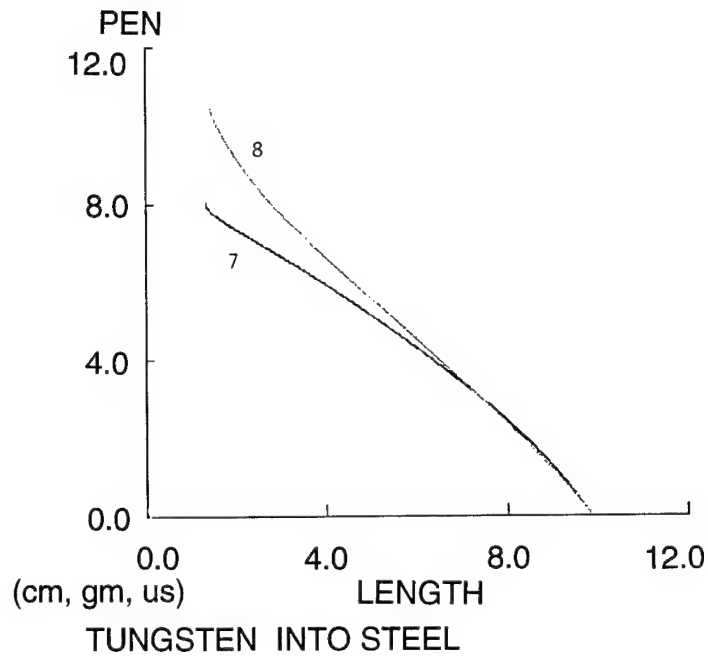


Fig. 2.4. Runs 7 and 8.

Figs. 2.1 to 2.4. Penetration-erosion curves (2.1 is for runs 1 and 4, 2.2 is for runs 2 and 5, 2.3 is for runs 3 and 6, and 2.4 is for runs 7 and 8).

Figs 2.1 and 2.4 are for $V = 1.5$ km/s, for steel into steel and tungsten alloy into steel, respectively. We see that in both cases, the planar symmetry projectile has about 30% advantage over the axial symmetry projectile. In Figs. 2.2 and 2.3 we see that for $V = 2.0$ km/s the advantage decreases to about 10%, and for $V = 2.5$ km/s it decreases to about 5%. The penetration results (P_i) for all 8 runs are given in Table 4.

Table 4
Penetration Results

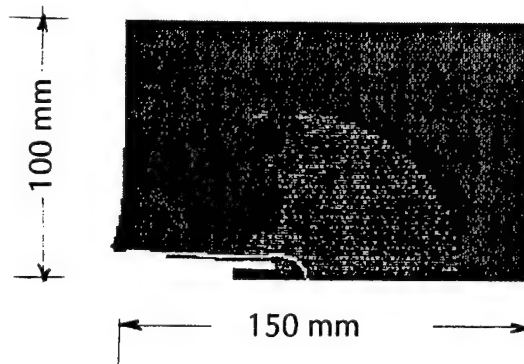
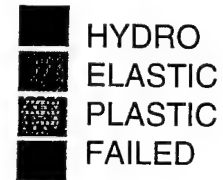
| Run No. | V(km/s) | Pf/Lo | Proj. Mat. |
|---------|---------|-------|----------------|
| 1 | 1.5 | 0.38 | steel |
| 2 | 1.5 | 0.51 | " |
| 3 | 2.0 | 0.65 | " |
| 4 | 2.0 | 0.71 | " |
| 5 | 2.5 | 0.80 | " |
| 6 | 2.5 | 0.84 | " |
| 7 | 1.5 | 0.80 | Tungsten alloy |
| 8 | 1.5 | 1.04 | " |

Observing the plots in Appendix A, we notice substantial differences in the penetration process characteristics between the two symmetries.

The first difference has to do with lateral confinement. In Fig. 3, we show plots of material status at 1000 cycles for runs 7 and 8 (tungsten alloy into steel at 1.5 km/s). We see that while for axial symmetry a target of $Dt/2 = 100$ mm, $Lt = 150$ mm provides practically full confinement, for planar symmetry, even a target as large as $Dt/2 = 280$ mm, $Lt = 280$ is not enough, as the upper and back boundaries have moved. We also see that the lip around the crater on the front boundary is much larger for planar symmetry. It's about 5 times larger (in linear dimensions).

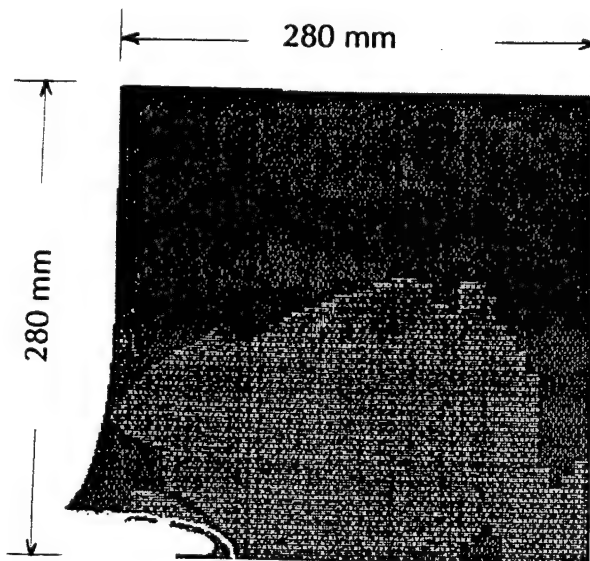
TUNGSTEN INTO STEEL

MATERIAL STATUS



(cm, gm, us)
CYCLE 1000
T = 1.000E+02

Axial, 7



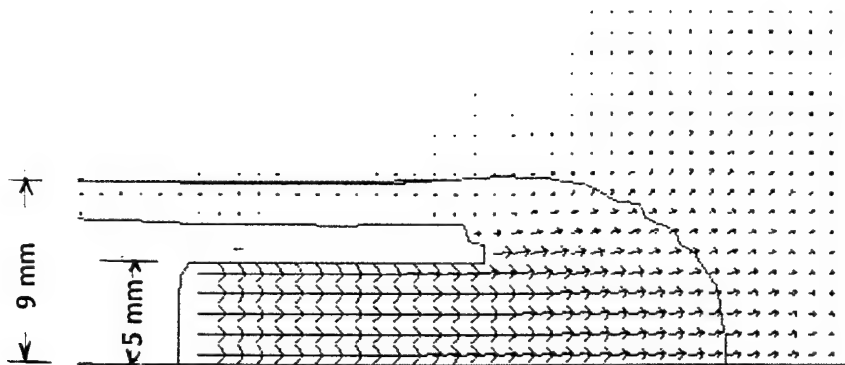
(cm, gm, us)
CYCLE 1000
T = 1.002E+02

Planar, 8

Fig. 3. Material status for runs 7 and 8 at 1000 cycles ($\sim 100 \mu s$).

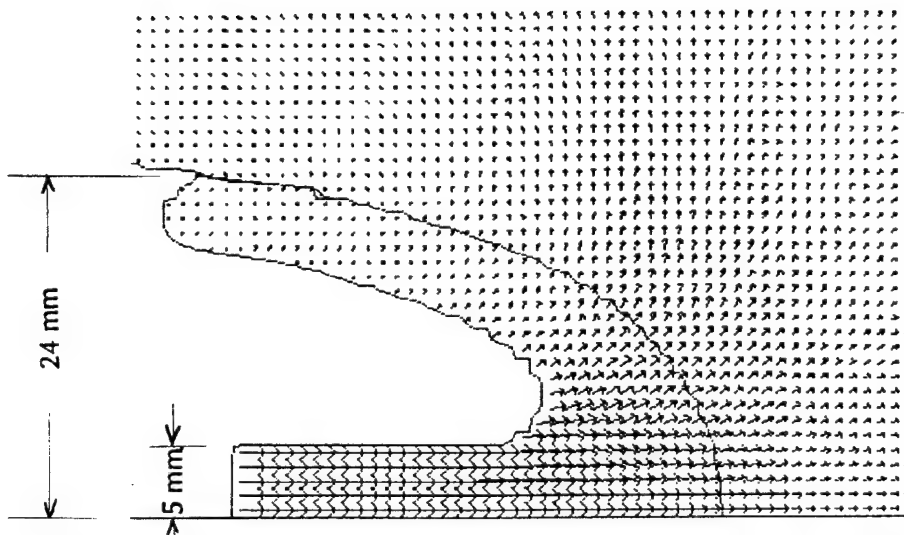
The second difference has to do with crater dimensions. Both size and shape are different. As an example, we show in Fig. 4 detailed plots of the inner part of the crater in runs 7 and 8 at 1000 cycles. We see that while for axial symmetry the crater diameter is approximately constant and is about 1.8 times the projectile diameter (at 1.5 km/s) for planar symmetry the crater width is not constant, and at the entrance boundary it is about five times the projectile width. At this time, we don't have quantitative understanding or valid engineering models to account for these differences.

IMPACT INTO STEEL



CYCLE 1000
T = 1.000E+02

Axial, 7



CYCLE 1000
T = 1.000E+02

Planar, 8

Fig. 4. Crater geometry and velocity vectors for runs 7 and 8 at 1000 cycles ($\sim 100 \mu\text{s}$).

Conclusions

We used AUTODYN2D to simulate penetration of steel and tungsten alloy projectiles into steel targets for axial and planar symmetries. The purpose was to see to what extent the planar projectiles have an advantage over circular projectiles.

We found that:

- Planar projectiles penetrate more than circular projectiles at low velocities (1.5 km/s).
- Planar projectiles lose their advantage with increasing velocity.

| Velocity km/s | Advantage of Planar Projectiles |
|---------------|------------------------------------|
| 1.5 | 30% |
| 2.0 | 10% |
| 2.5 | 5% |

- Much larger target dimensions are needed for full confinement of planar projectiles.
- Craters created by planar projectiles are much wider and their width is not constant.

Acknowledgments

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Appendix A

Material status and velocity vector plots for runs 1 to 8.

Appendix A is included in only 2 copies of this report.

Runs 1 to 8 are characterized in Table 3.

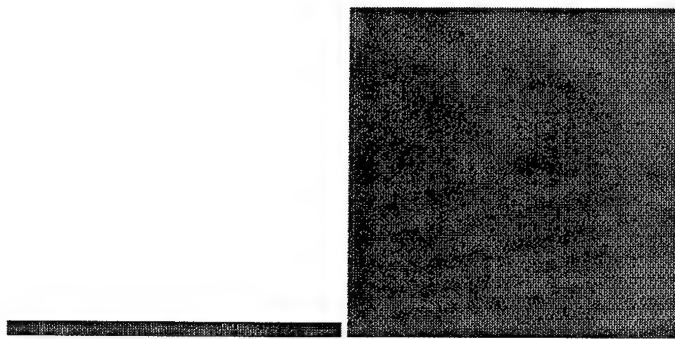
Appendix A1

Plots for run No. 1

Steel projectile

Axial symmetry

1.5 km/s

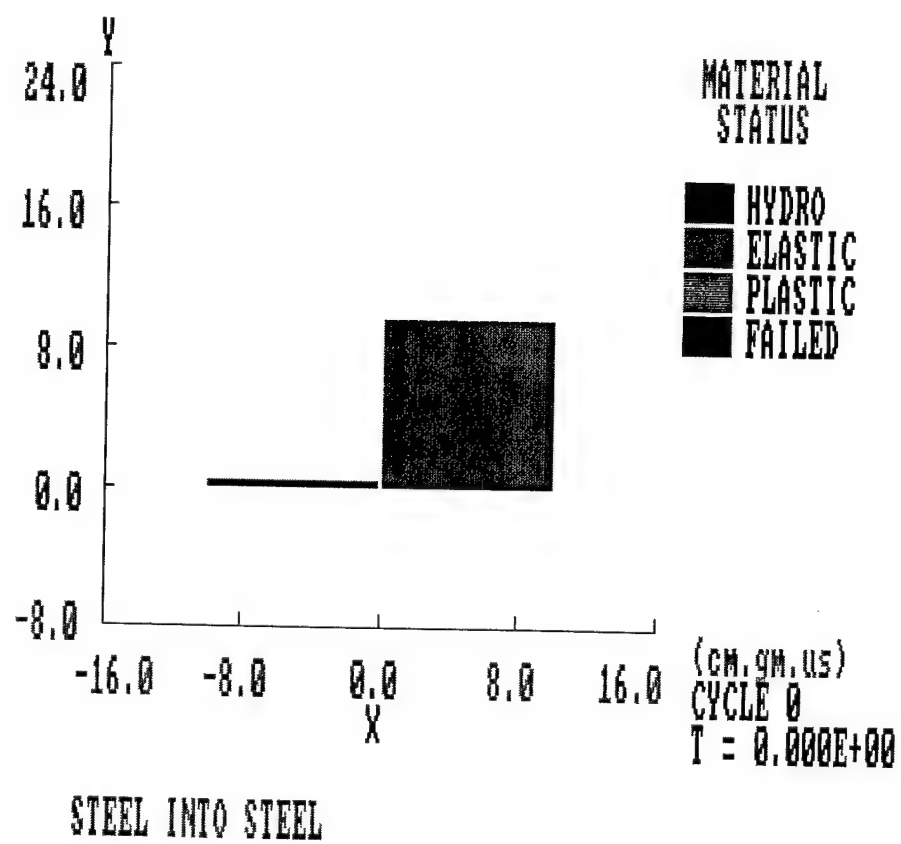


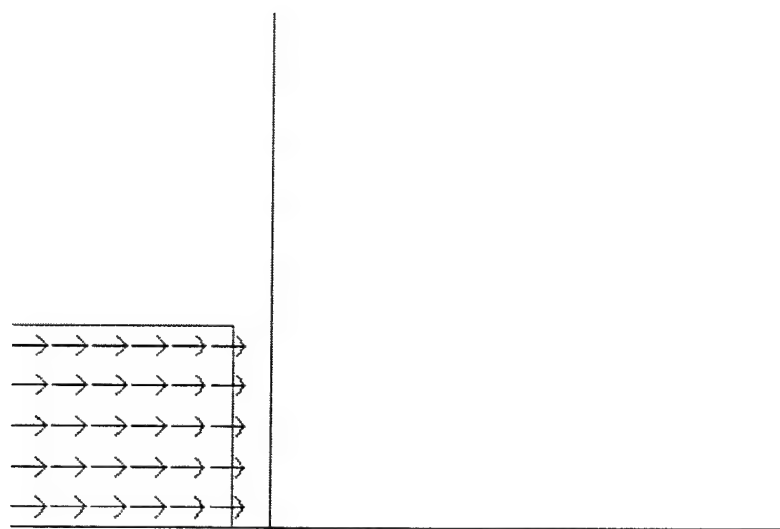
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM,GM,US)
CYCLE 0
T = 0.000E+00

STEEL INTO STEEL





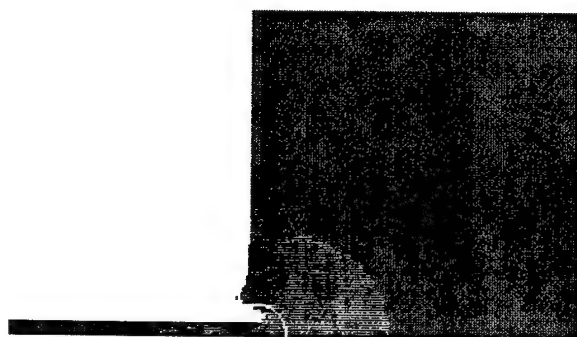
VELOCITY
VECTORS

Scale
→
0.000E-01

Maximum
Velocity
1.500E-01

Scale
4.500E-01
(cm, gm, us)
CYCLE 0
T = 0.000E+00

STEEL INTO STEEL

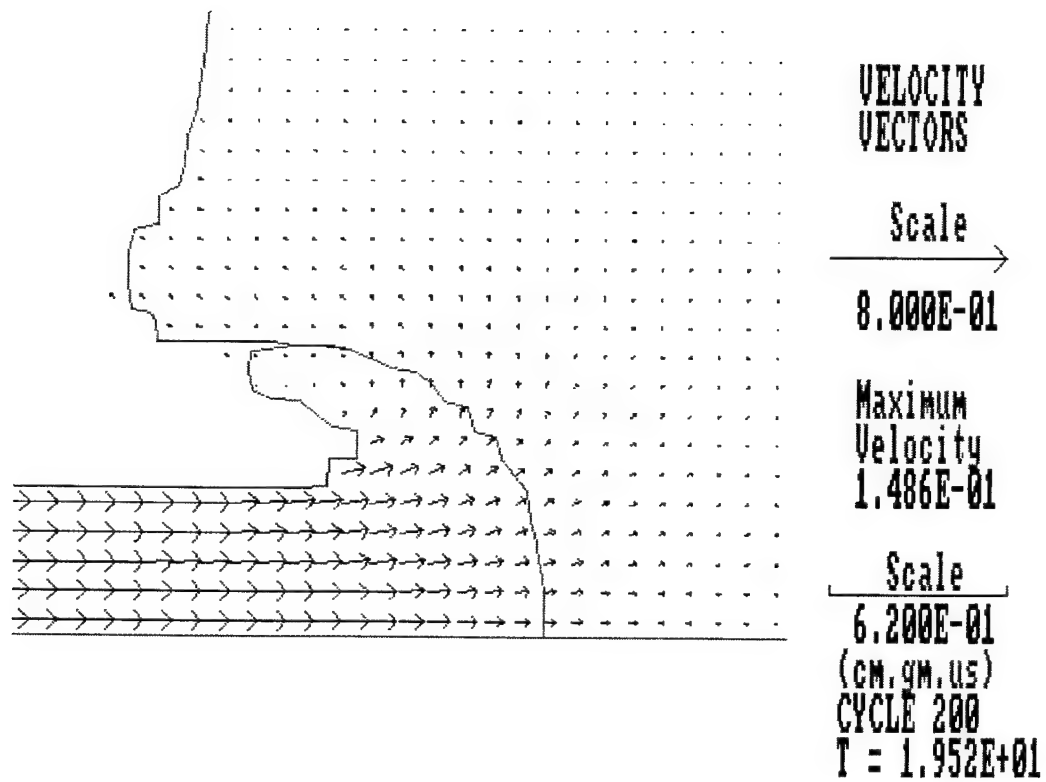


MATERIAL
STATUS

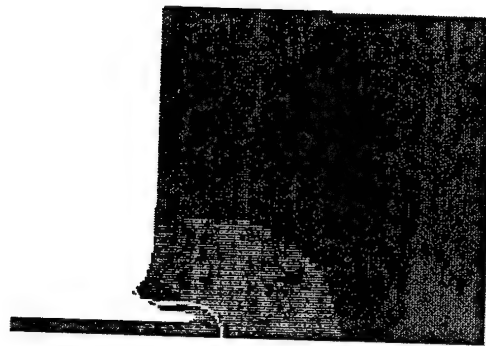
■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM, GM, US)
CYCLE 200
T = 1.952E+01

STEEL INTO STEEL



STEEL INTO STEEL

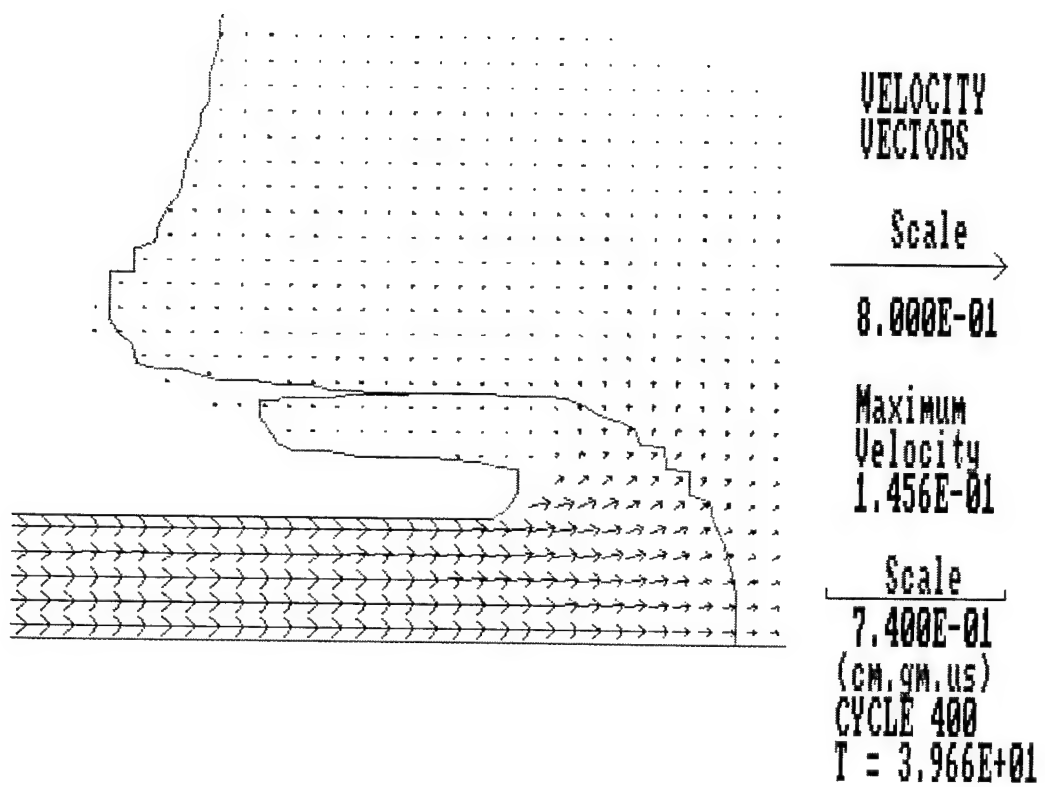


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 400
T = 3.966E+01

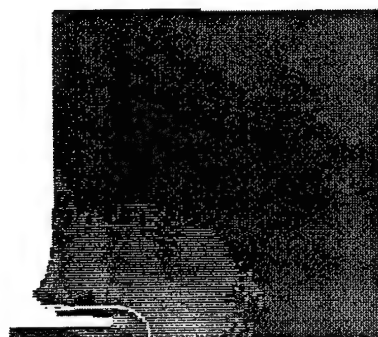
STEEL INTO STEEL



STEEL INTO STEEL

MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

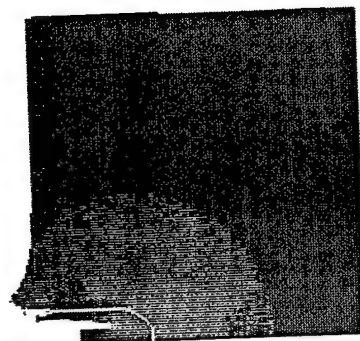


(CM, GM, US)
CYCLE 600
T = 5.996E+01

STEEL INTO STEEL

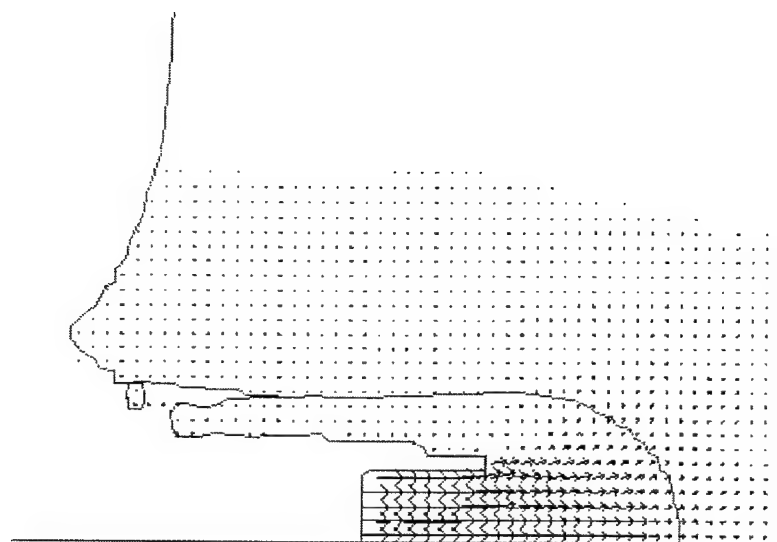
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM, GM, US)
CYCLE 800
T = 8.057E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.456E-01

Scale

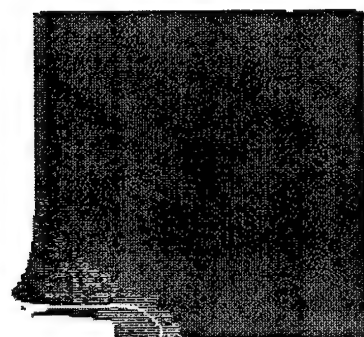
1.200E+00

(CM, GM, US)

CYCLE 800

T = 8.057E+01

STEEL INTO STEEL



MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM.GM.US)
CYCLE 1000
T = 1.032E+02

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.456E-01

Scale

1.300E+00

(cm, gm, us)

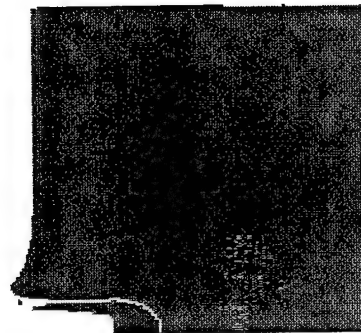
CYCLE 1000

T = 1.032E+02

STEEL INTO STEEL

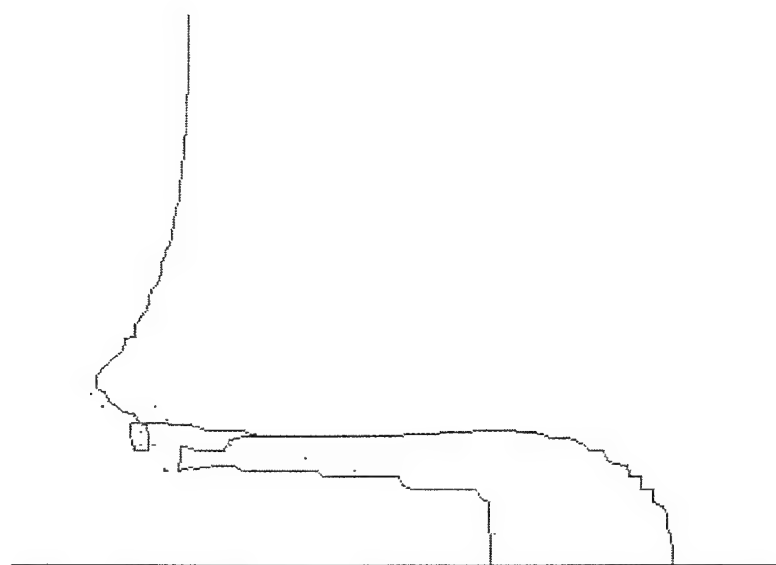
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(cm, gm, us)
CYCLE 1100
T = 1.150E+02

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.456E-01

Scale

1.400E+00

(cm, gm, us)

CYCLE 1100

T = 1.150E+02

STEEL INTO STEEL

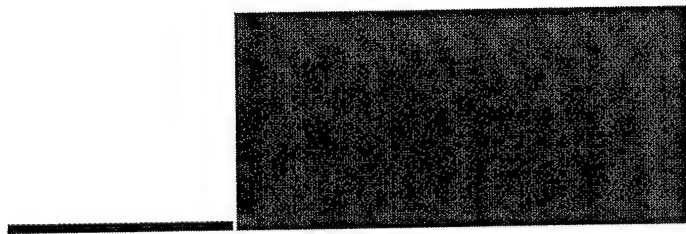
Appendix A2

Plots for run No. 2

Steel projectile

Axial symmetry

2.0 km/s

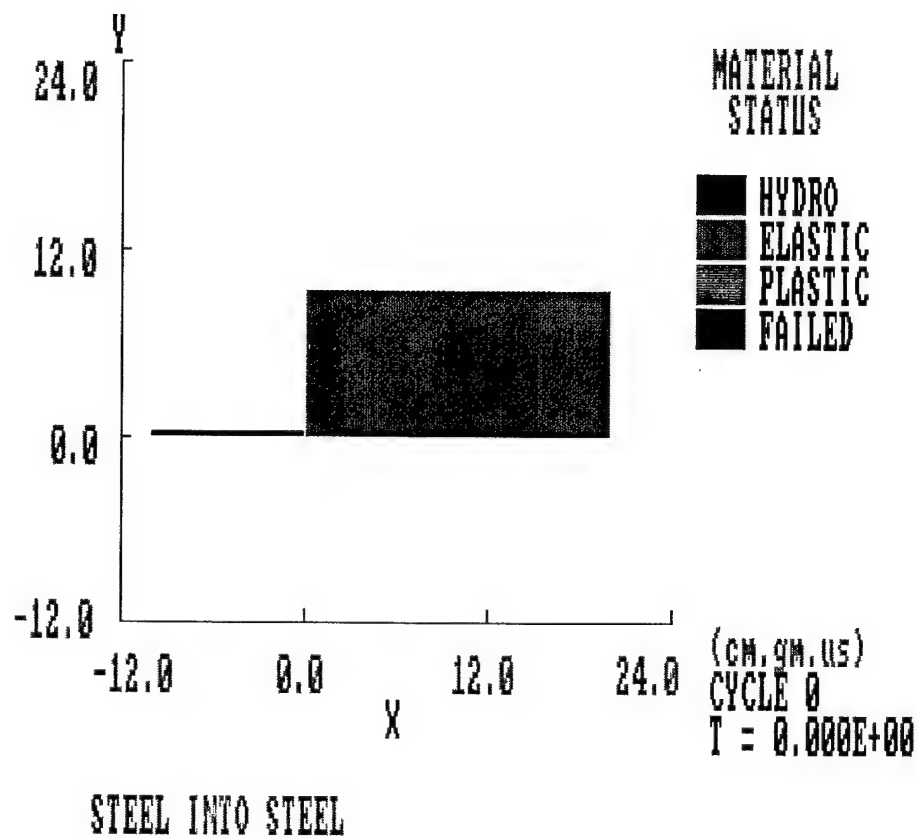


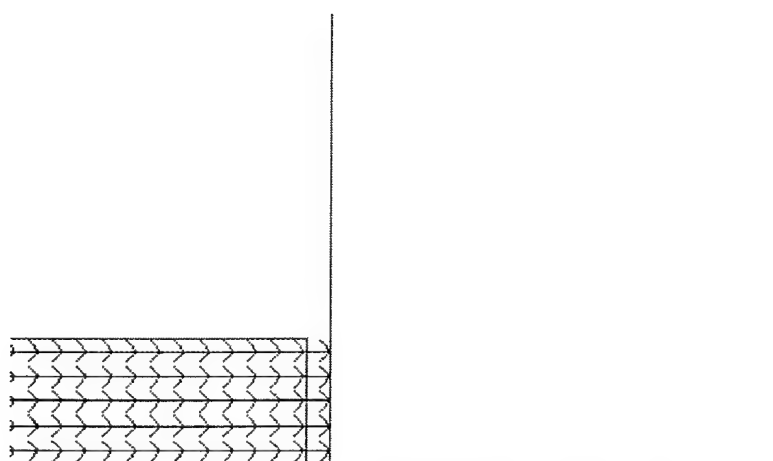
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM,GM,US)
CYCLE 0
T = 0.000E+00

STEEL INTO STEEL





VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
2.000E-01

Scale

7.300E-01

(cm, gm, us)

CYCLE 0

T = 0.000E+00

STEEL INTO STEEL

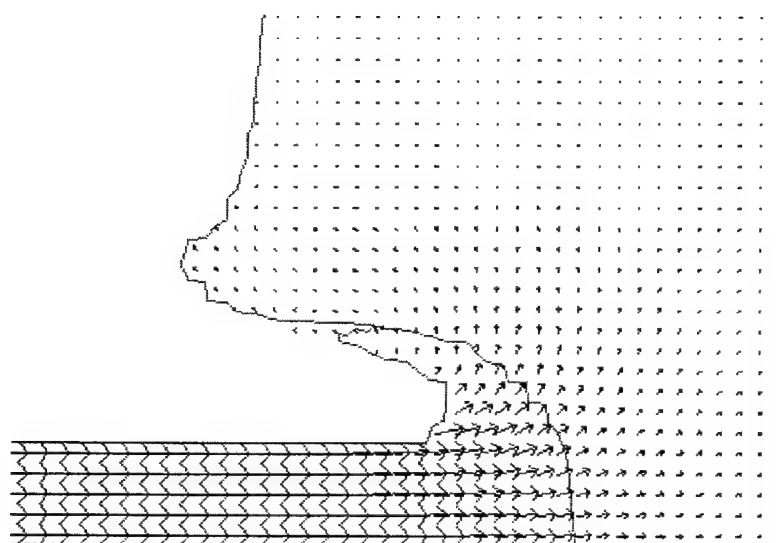


MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM.GM.US)
CYCLE 200
T = 1.813E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.994E-01

Scale

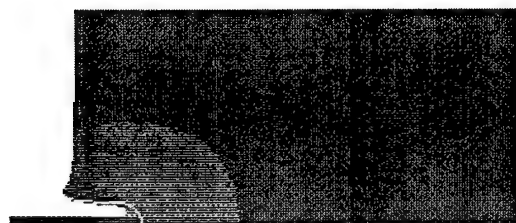
8.900E-01

(cm, gm, us)

CYCLE 200

T = 1.813E+01

STEEL INTO STEEL

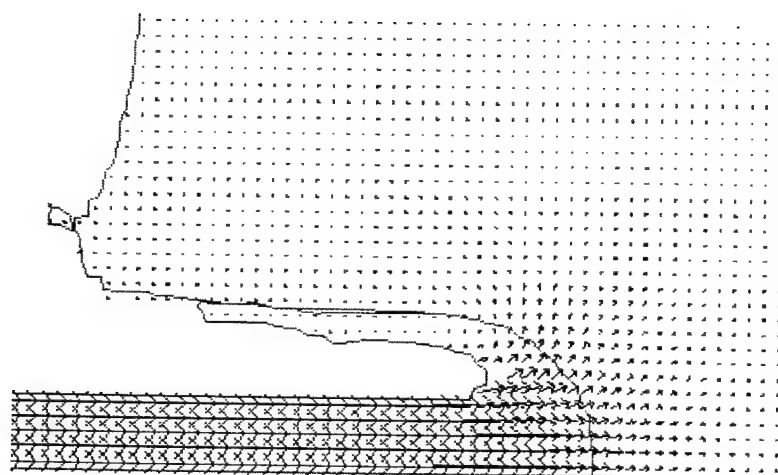


MATERIAL
STATUS

 HYDRO
 ELASTIC
 PLASTIC
 FAILED

(cm, gm, us)
 CYCLE 400
 T = 3.684E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.984E-01

Scale

1.200E+00

(cm, gm, us)

CYCLE 400

T = 3.684E+01

STEEL INTO STEEL

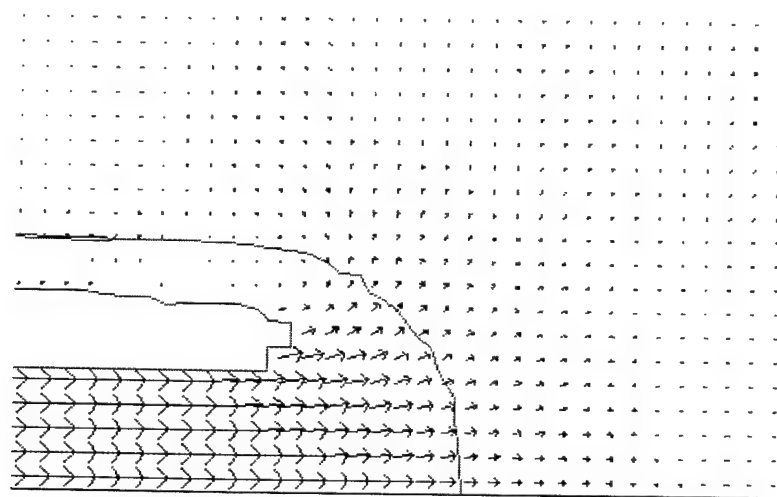


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 600
T = 5.570E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.984E-01

Scale

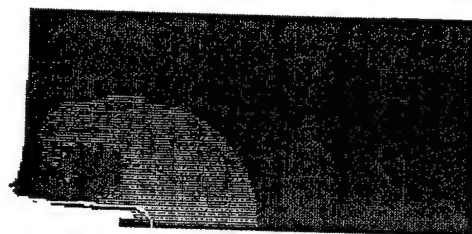
7.600E-01

(CM. GM. US)

CYCLE 600

T = 5.570E+01

STEEL INTO STEEL

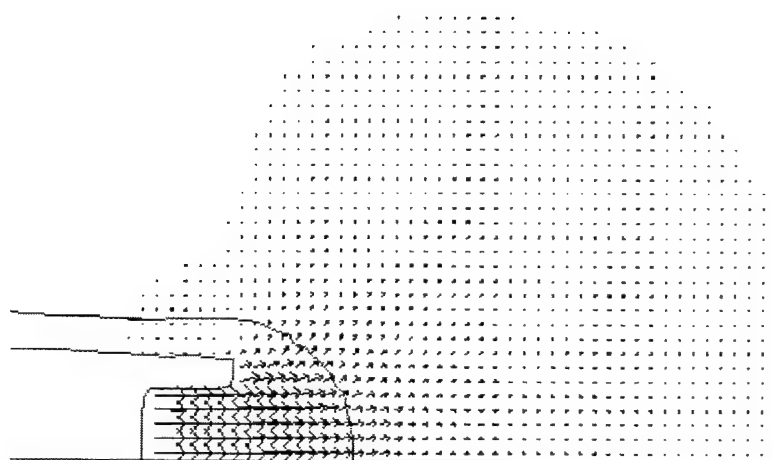


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 800
T = 7.488E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.984E-01

Scale

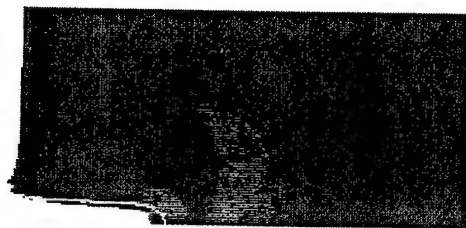
1.200E+00

(cm, gm, us)

CYCLE 800

T = 7.488E+01

STEEL INTO STEEL

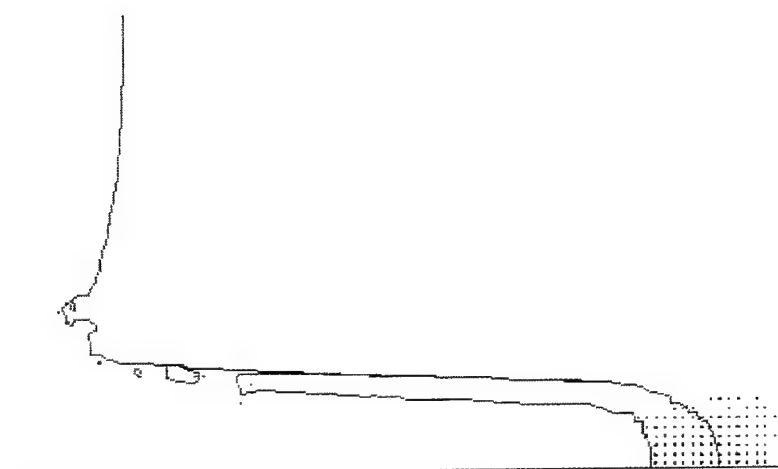


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM.GM.US)
CYCLE 990
T = 9.575E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.984E-01

Scale

1.900E+00

(CM, GM, US)

CYCLE 990

T = 9.575E+01

STEEL INTO STEEL

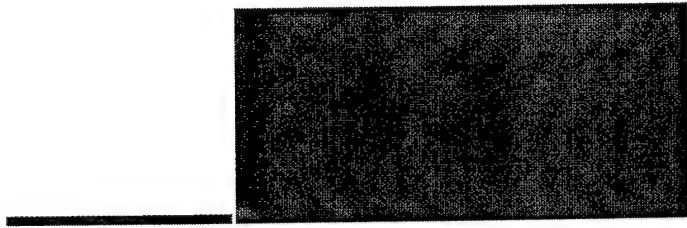
Appendix A3

Plots for run No. 3

Steel projectile

Axial symmetry

2.5 km/s

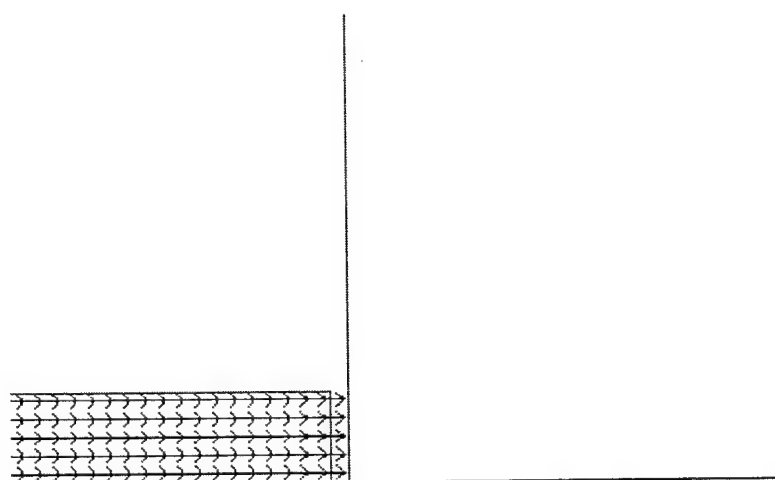


MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM, GM, US)
CYCLE 0
T = 0.000E+00

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.500E-01

Scale

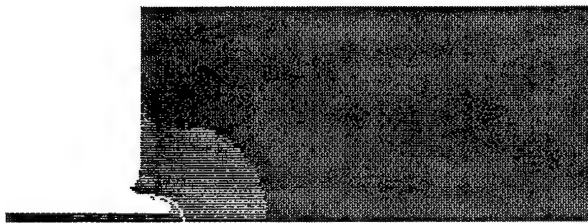
1.000E+00

(cm, gm, us)

CYCLE 0

T = 0.000E+00

STEEL INTO STEEL

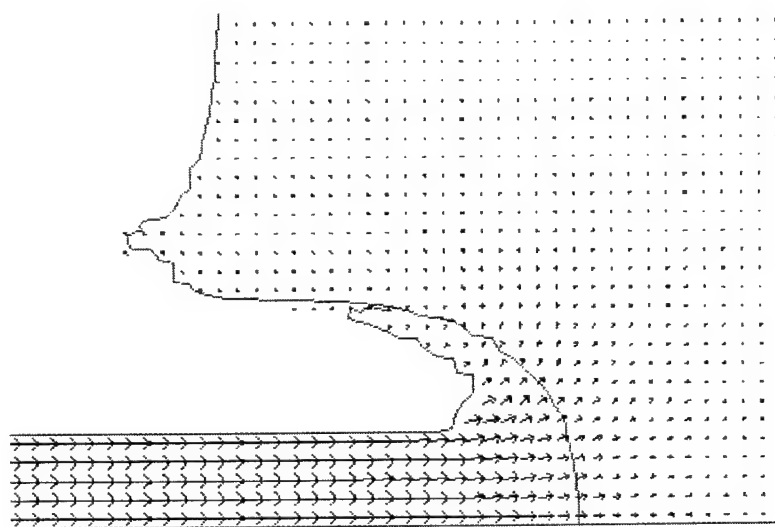


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 200
T = 1.692E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.498E-01

Scale

9.600E-01

(cm, gm, us)

CYCLE 200

T = 1.692E+01

STEEL INTO STEEL

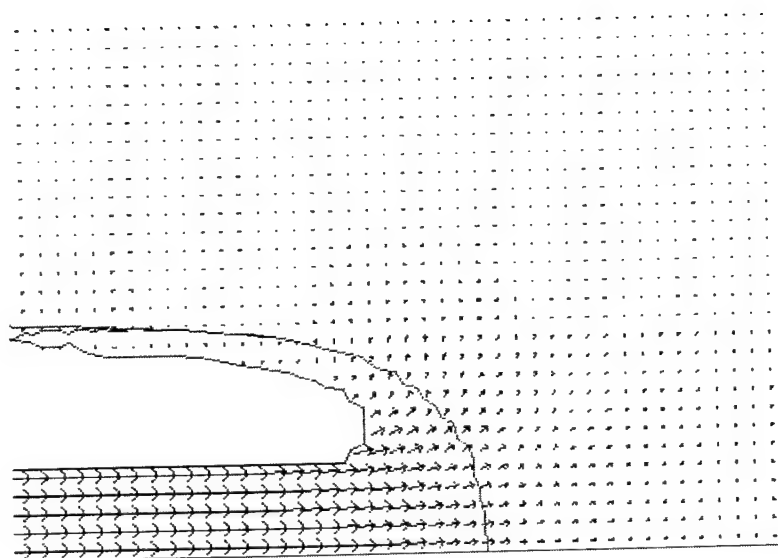


MATERIAL
STATUS

- HYDRO
- ELASTIC
- PLASTIC
- FAILED

(CM, GM, US)
CYCLE 400
T = 3.439E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.480E-01

Scale

9.800E-01

(cm, gm, us)

CYCLE 400

T = 3.439E+01

STEEL INTO STEEL

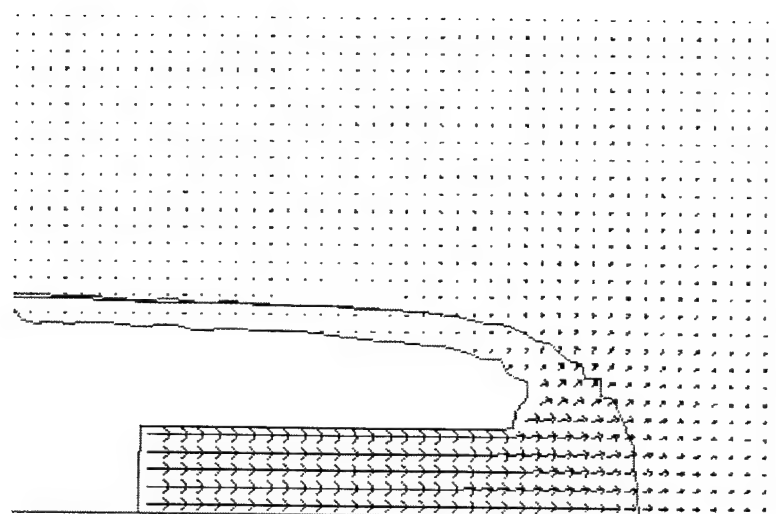


MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(cm, gm, us)
CYCLE 600
T = 5.201E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.480E-01

Scale

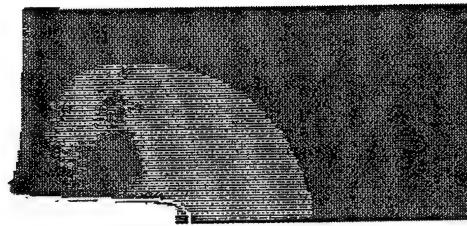
1.000E+00

(cm, gm, us)

CYCLE 600

T = 5.201E+01

STEEL INTO STEEL

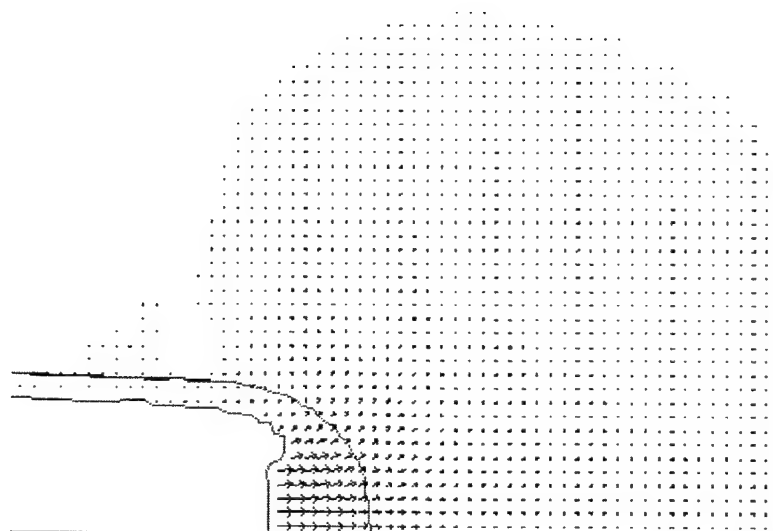


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 800
T = 7.015E+01

STEEL INTO STEEL



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.480E-01

Scale

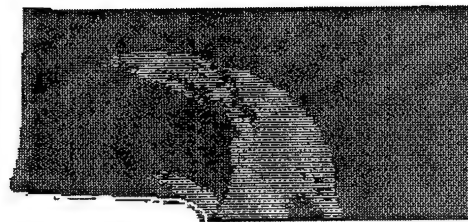
1.300E+00

(cm, gm, us)

CYCLE 800

T = 7.015E+01

STEEL INTO STEEL

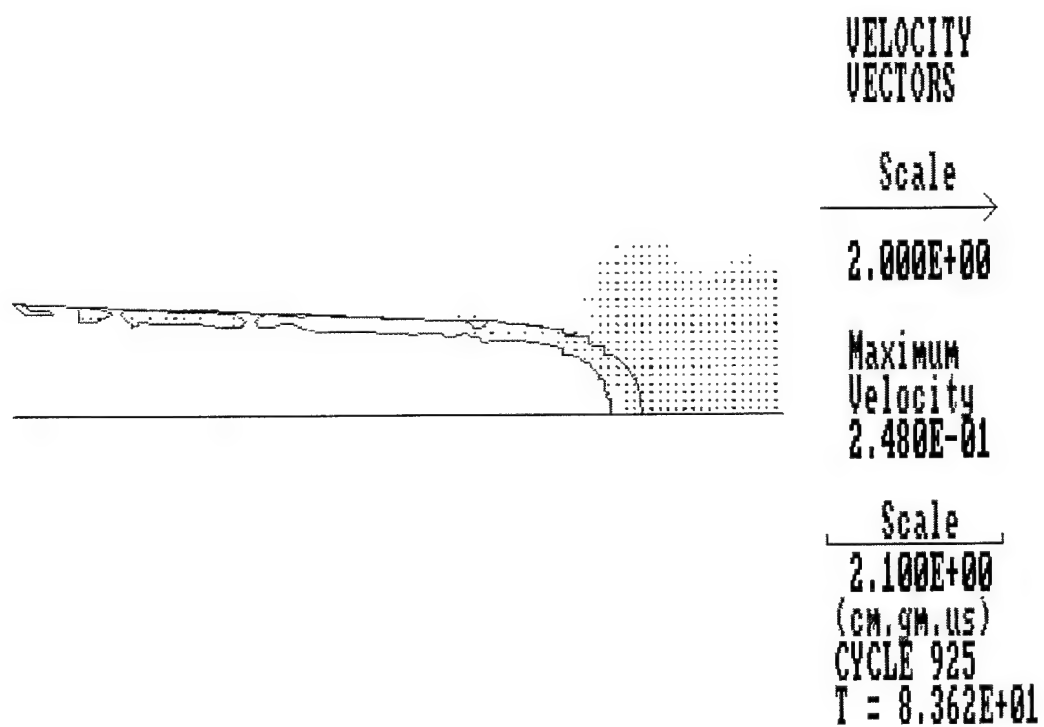


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 925
T = 8.362E+01

STEEL INTO STEEL



STEEL INTO STEEL

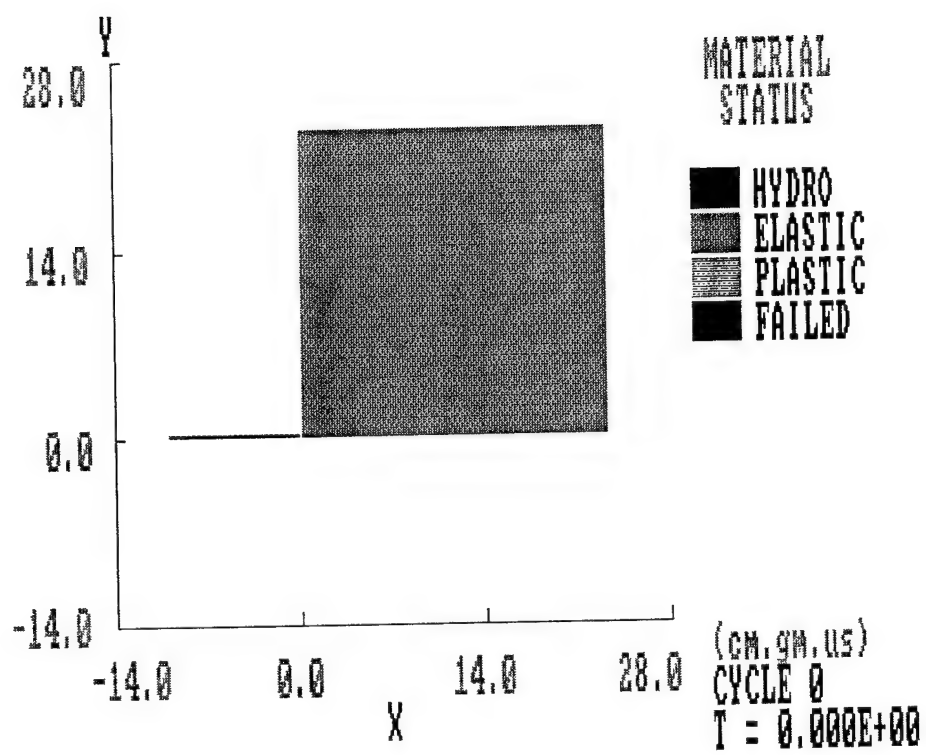
Appendix A4

Plots for run No. 4

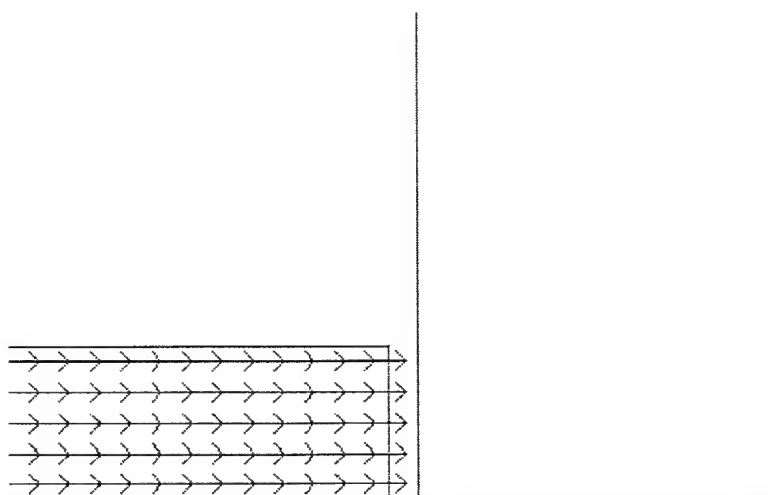
Steel projectile

Planar symmetry

1.5 km/s



STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.500E-01

Scale

5.800E-01

(cm, gm, us)

CYCLE 0

T = 0.000E+00

STEEL INTO STEEL PLANAR

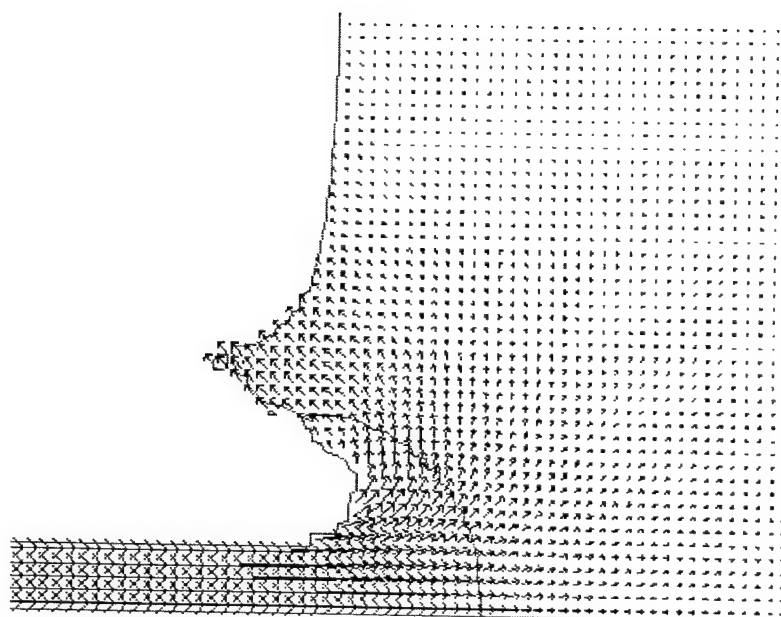


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 200
T = 1.941E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.482E-01

Scale

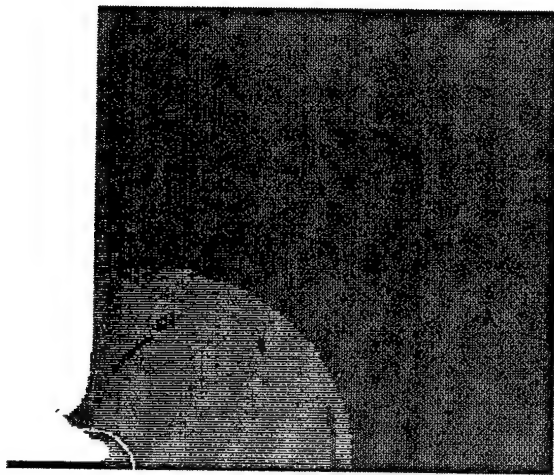
1.300E+00

(cm, gm, us)

CYCLE 200

T = 1.941E+01

STEEL INTO STEEL PLANAR

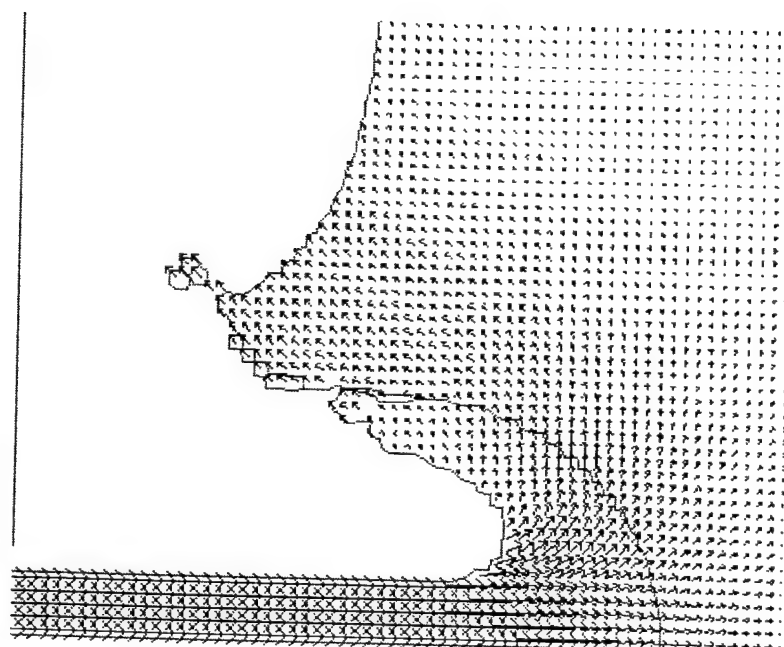


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 400
T = 3.958E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.457E-01

Scale

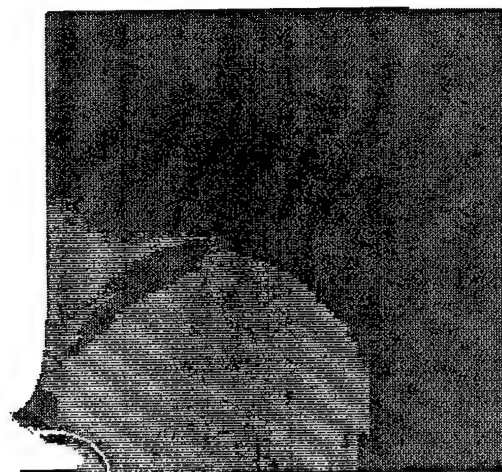
1.400E+00

(CM, GM, US)

CYCLE 400

T = 3.958E+01

STEEL INTO STEEL PLANAR

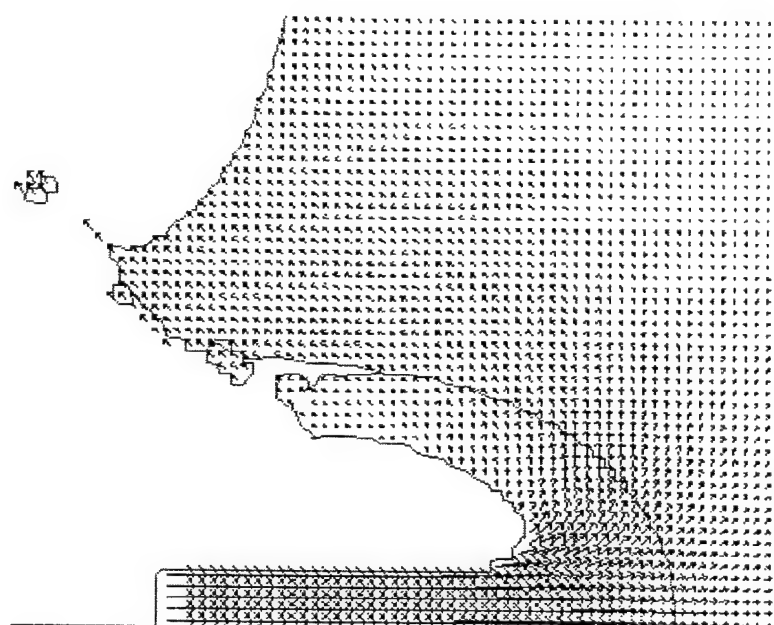


MATERIAL
STATUS

 HYDRO
 ELASTIC
 PLASTIC
 FAILED

(CM, GM, US)
 CYCLE 600
 T = 5.995E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.457E-01

Scale

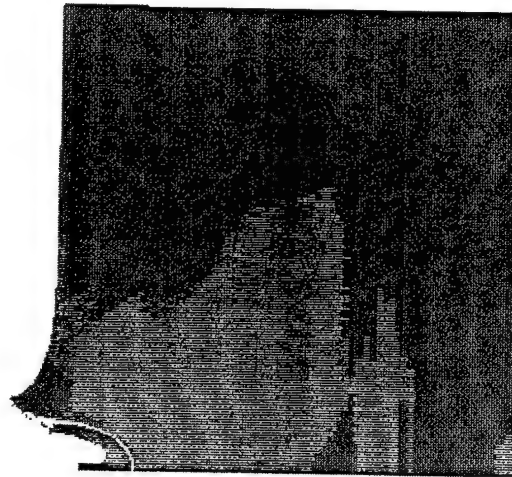
1.500E+00

(cm, gm, us)

CYCLE 600

T = 5.995E+01

STEEL INTO STEEL PLANAR

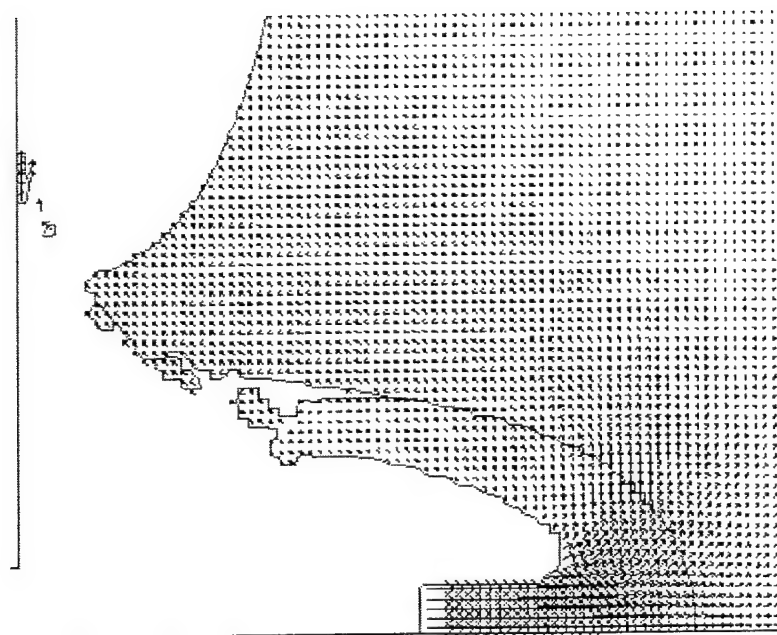


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 800
T = 8.074E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.457E-01

Scale

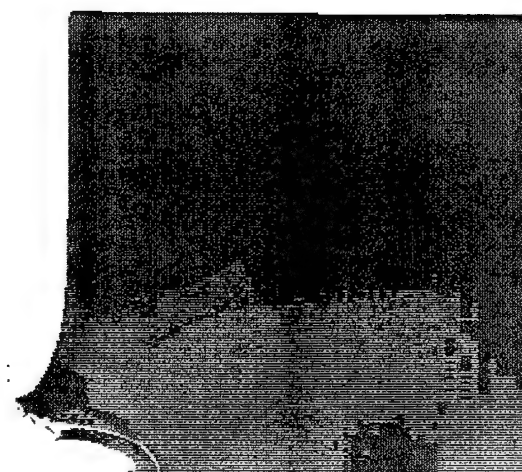
1.800E+00

(CM, GM, US)

CYCLE 800

T = 8.074E+01

STEEL INTO STEEL PLANAR

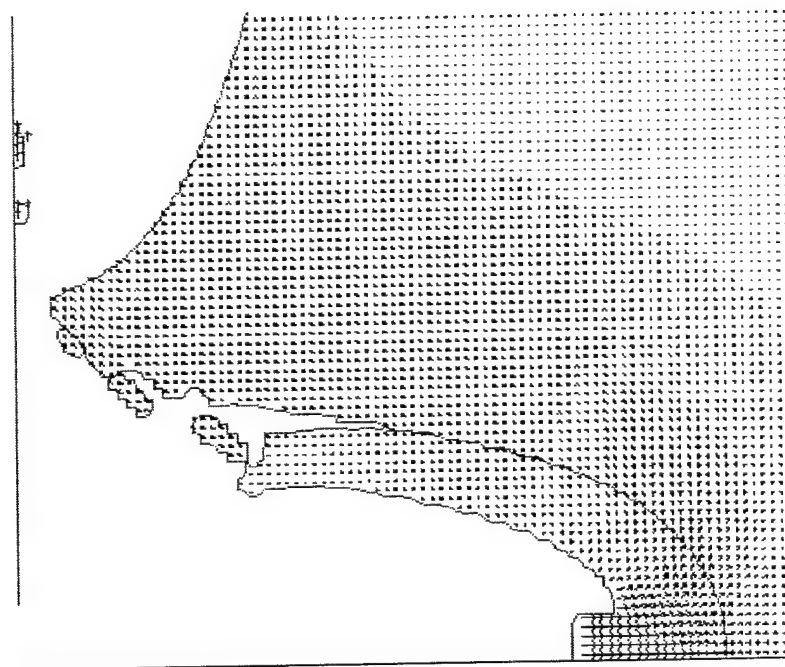


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 1000
T = 1.021E+02

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.457E-01

Scale

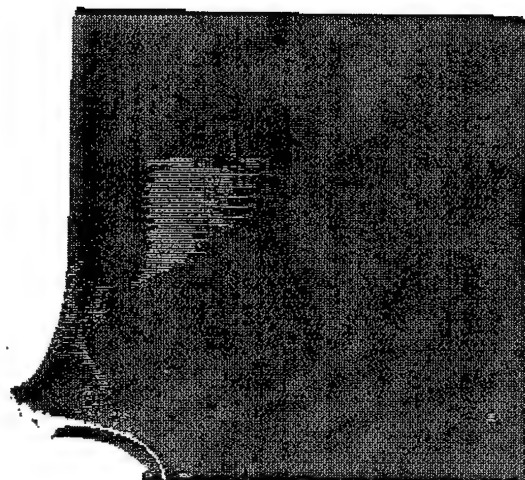
1.900E+00

(CM. GM. US)

CYCLE 1000

T = 1.021E+02

STEEL INTO STEEL PLANAR

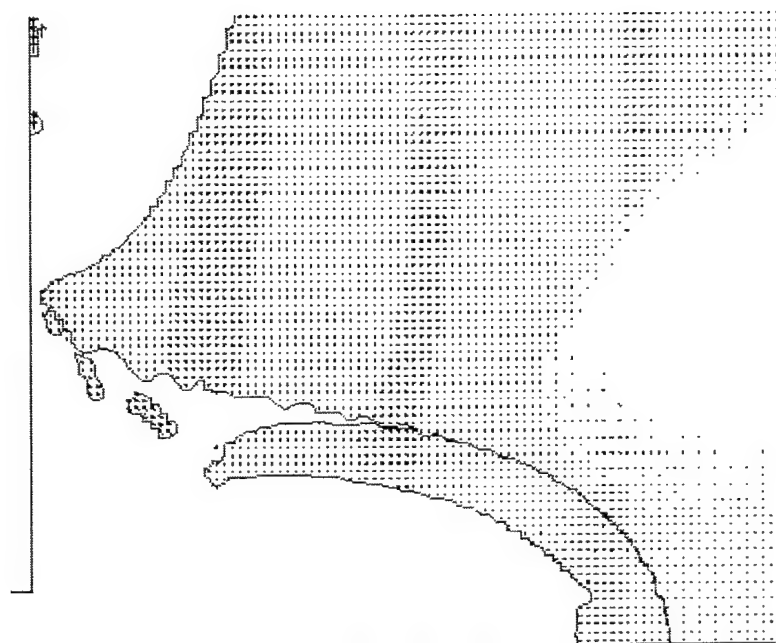


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 1400
T = 1.450E+02

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.457E-01

Scale

2.200E+00

(cm, gm, us)

CYCLE 1400

T = 1.450E+02

STEEL INTO STEEL PLANAR

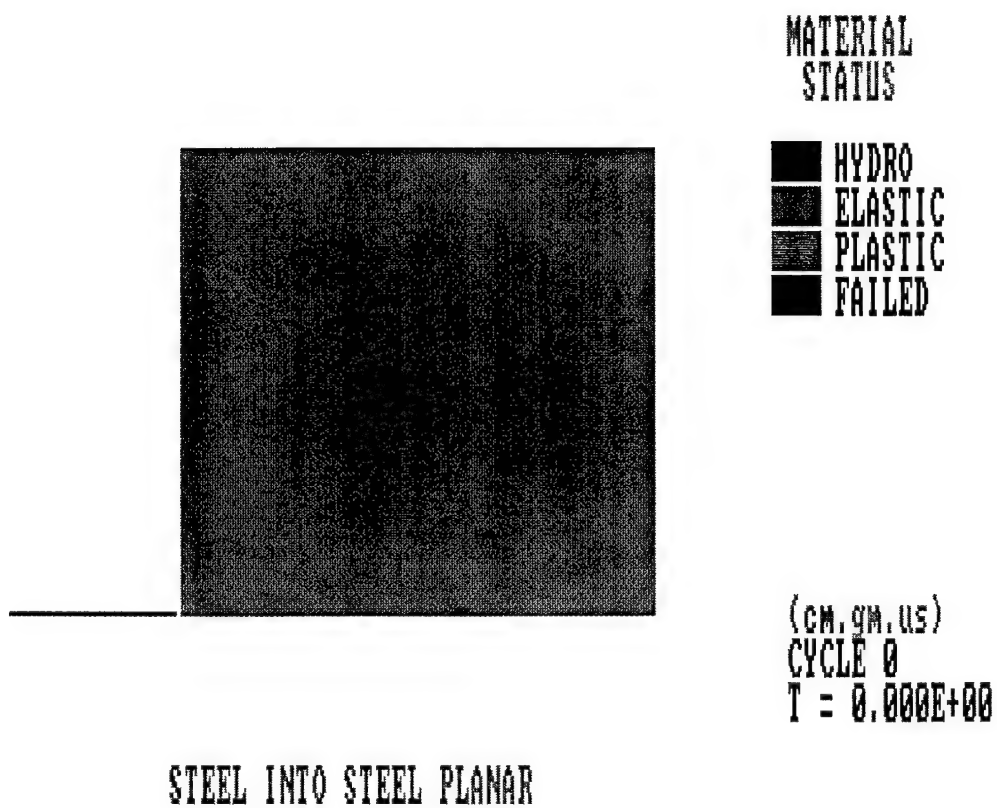
Appendix A5

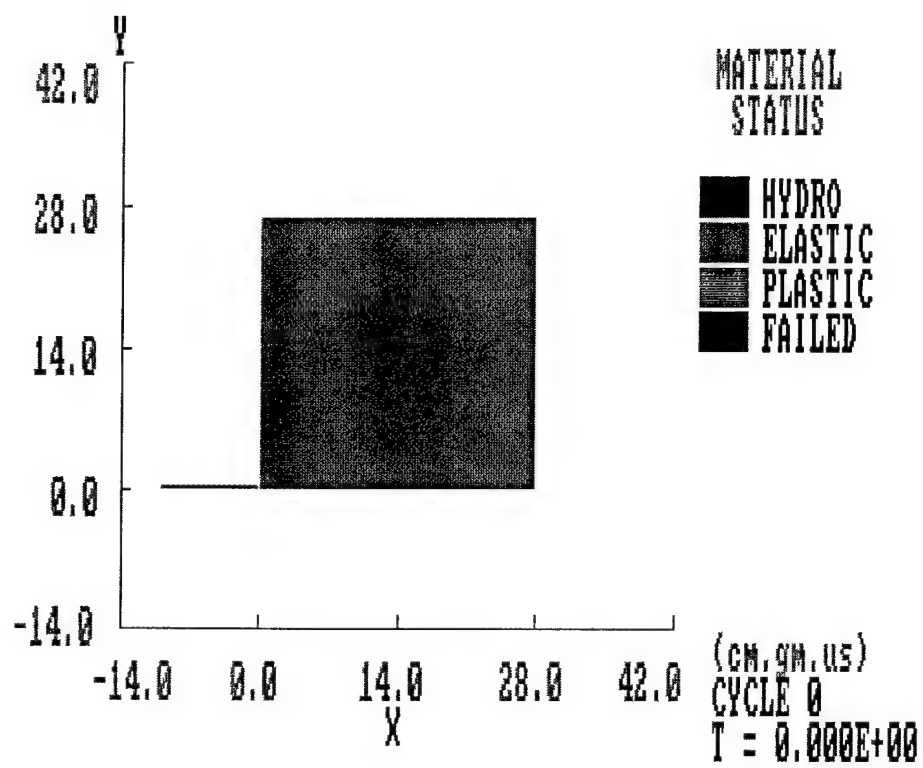
Plots for run No. 5

Steel projectile

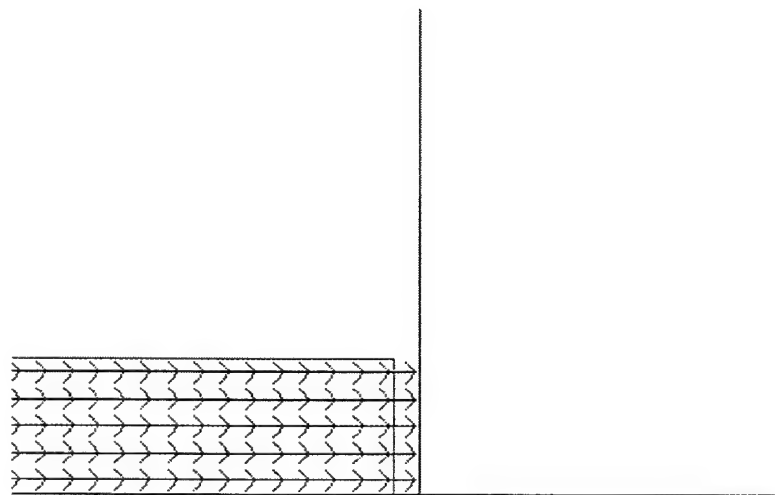
Planar symmetry

2.0 km/s





STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
2.000E-01

Scale

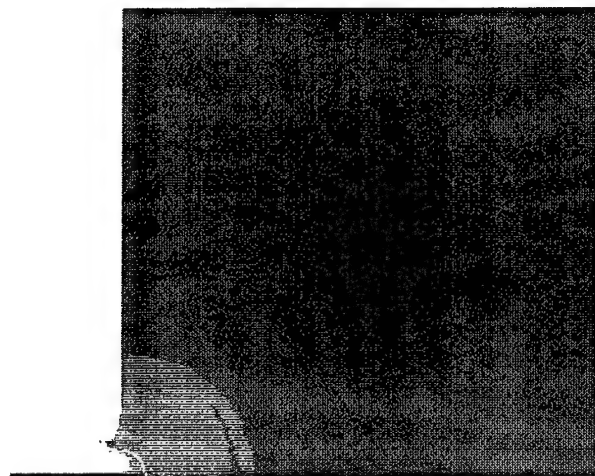
6.800E-01

(cm, gm, us)

CYCLE 0

T = 0.000E+00

STEEL INTO STEEL PLANAR

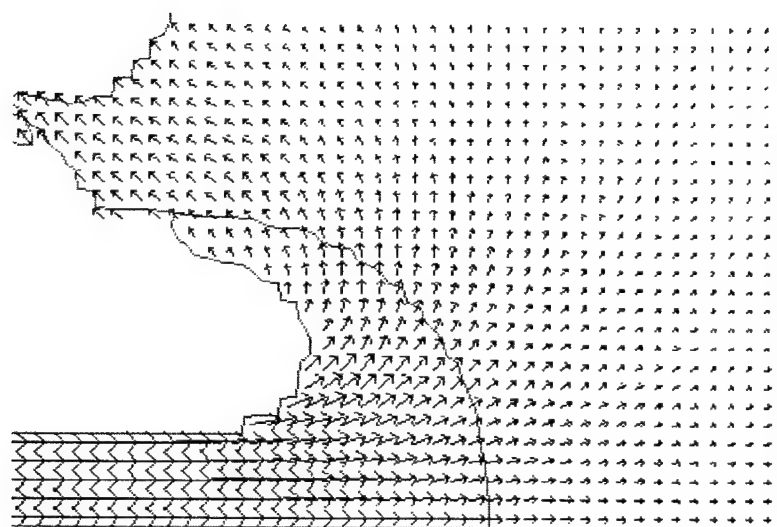


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(cm.gm.us)
CYCLE 200
T = 1.797E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.989E-01

Scale

9.700E-01

(cm, gm, us)

CYCLE 200

T = 1.797E+01

STEEL INTO STEEL PLANAR

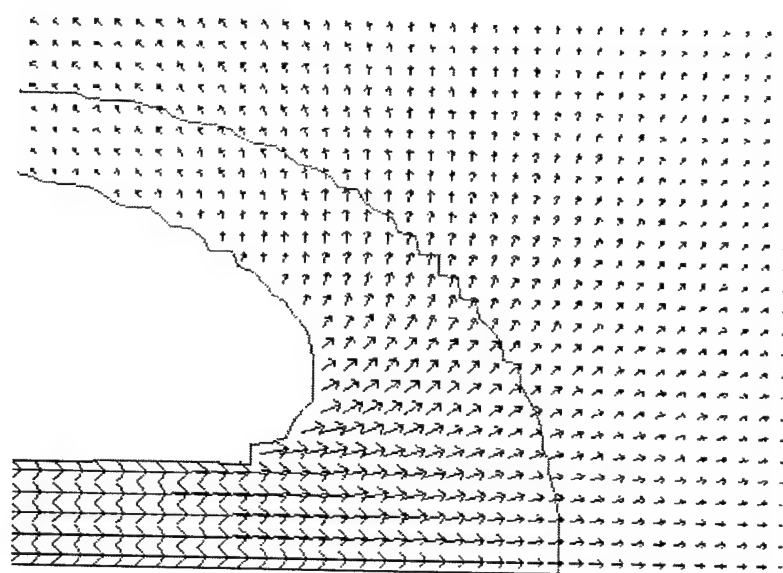


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 400
T = 3.672E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

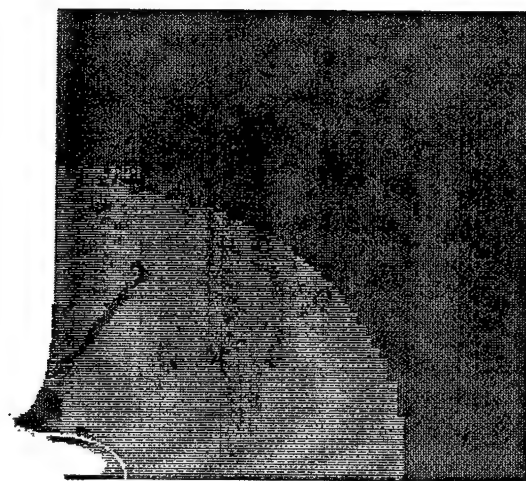
Scale

8.500E-01
(CM, GM, US)

CYCLE 400

T = 3.672E+01

STEEL INTO STEEL PLANAR

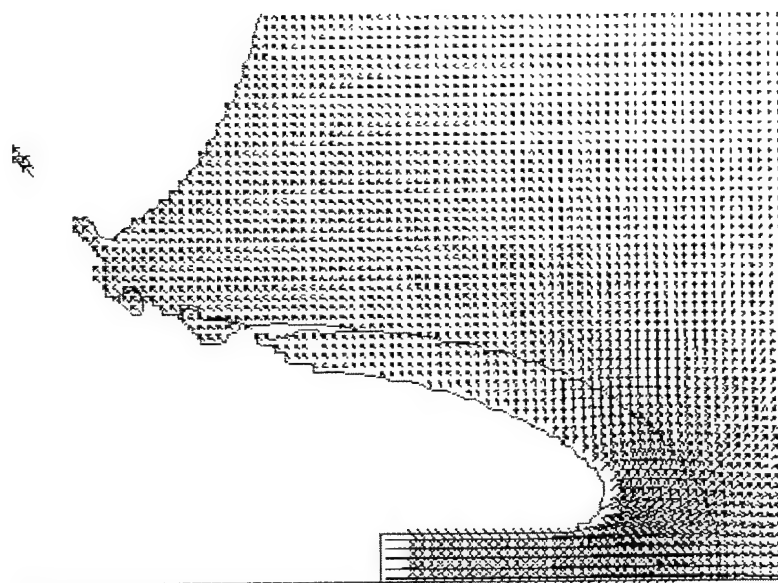


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 600
T = 5.567E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

Scale

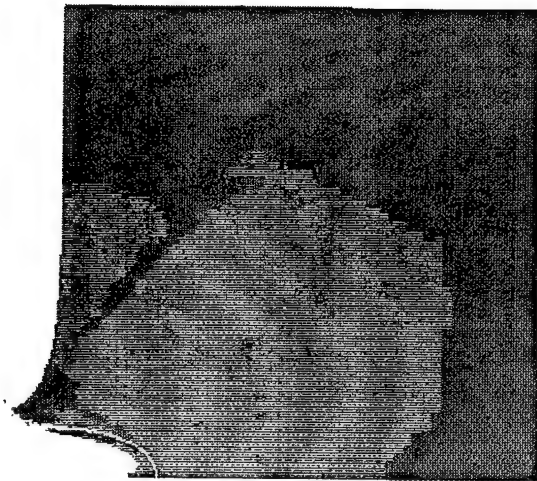
1.800E+00

(cm, gm, us)

CYCLE 600

T = 5.567E+01

STEEL INTO STEEL PLANAR

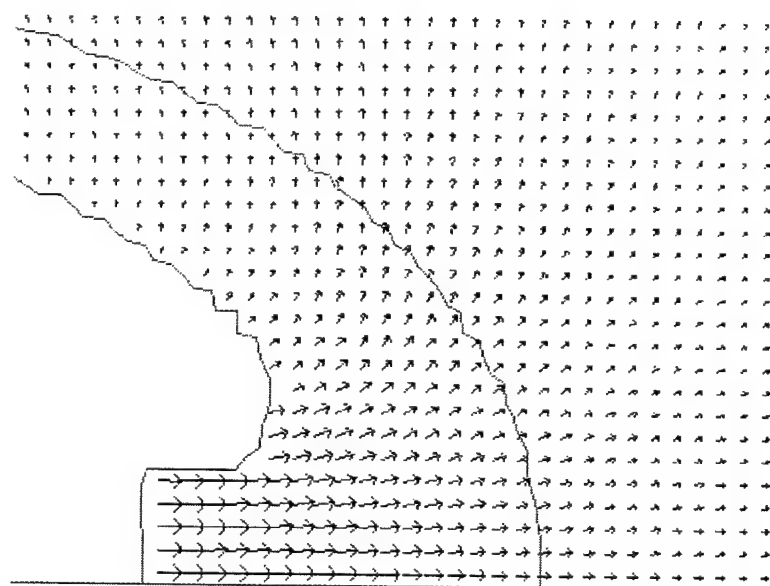


MATERIAL
STATUS

■ HYDRO
 ■ ELASTIC
 ■ PLASTIC
 ■ FAILED

(CM, GM, US)
 CYCLE 800
 T = 7.498E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

Scale

8.000E-01

(cm, gm, us)

CYCLE 800

T = 7.498E+01

STEEL INTO STEEL PLANAR



MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM, GM, US)
CYCLE 1000
T = 9.608E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

Scale

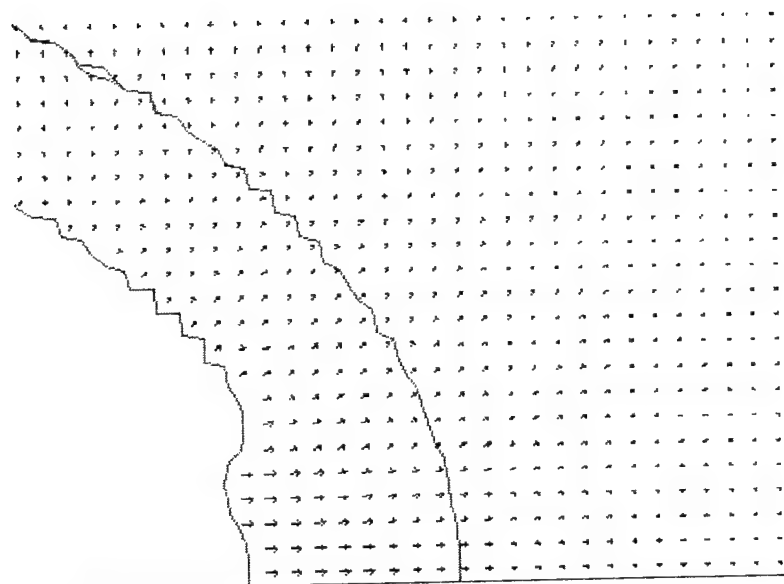
2.500E+00

(CM, GM, US)

CYCLE 1000

T = 9.608E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

Scale

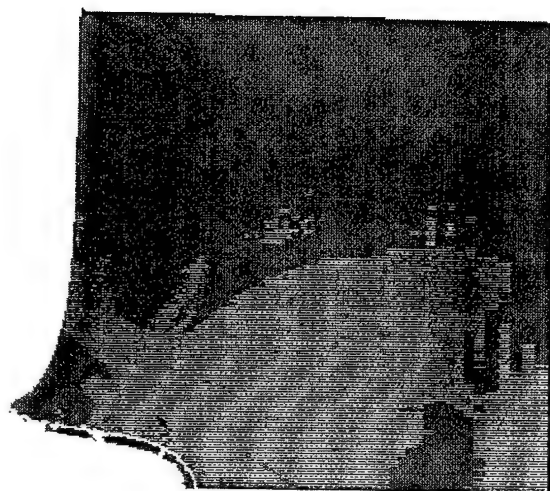
7.400E-01

(cm, gm, us)

CYCLE 1000

T = 9.608E+01

STEEL INTO STEEL PLANAR



MATERIAL
STATUS

■ HYDRO
 ■ ELASTIC
 ■ PLASTIC
 ■ FAILED

(cm, gm, us)
 CYCLE 1200
 T = 1.176E+02

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

1.000E+00

Maximum
Velocity
1.948E-01

Scale

2.900E+00

(cm, gm, us)

CYCLE 1200

T = 1.176E+02

STEEL INTO STEEL PLANAR

Appendix A6

Plots for run No. 6

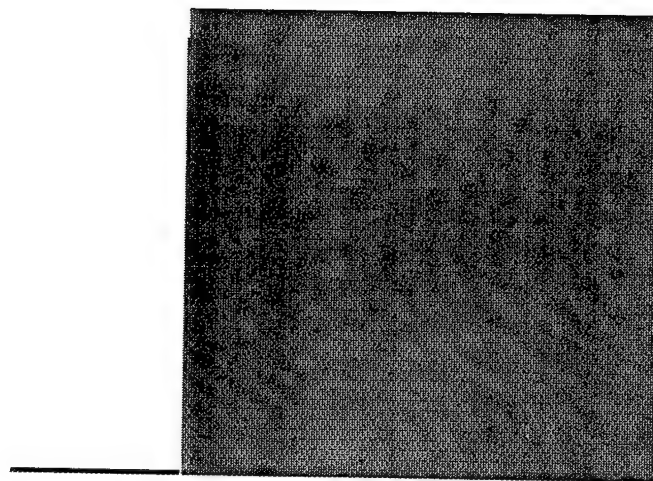
Steel projectile

Planar symmetry

2.5 km/s

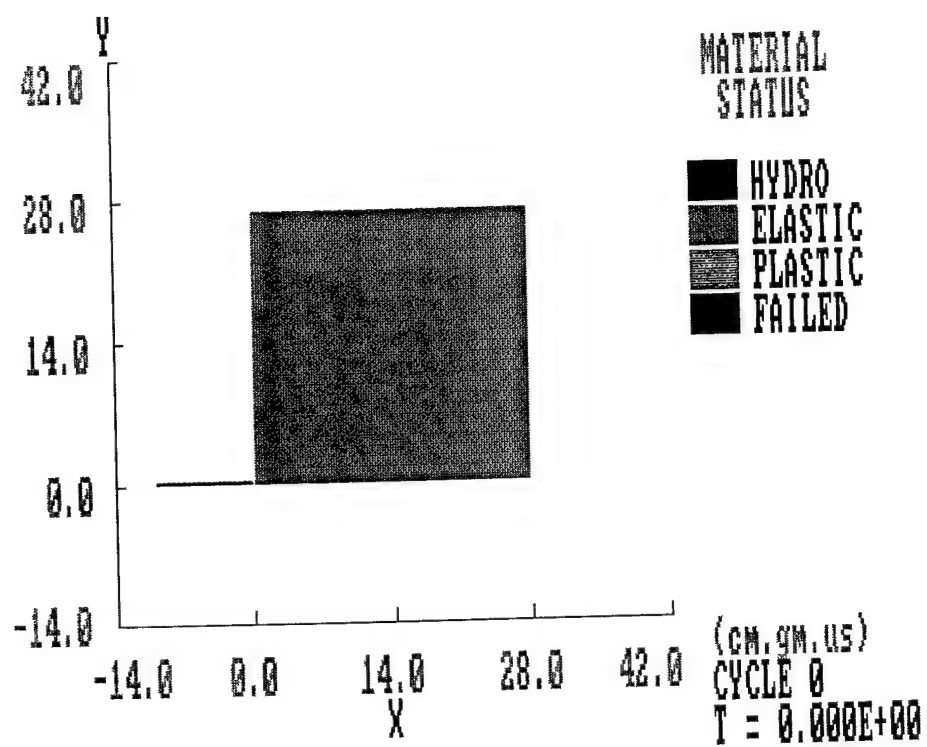
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

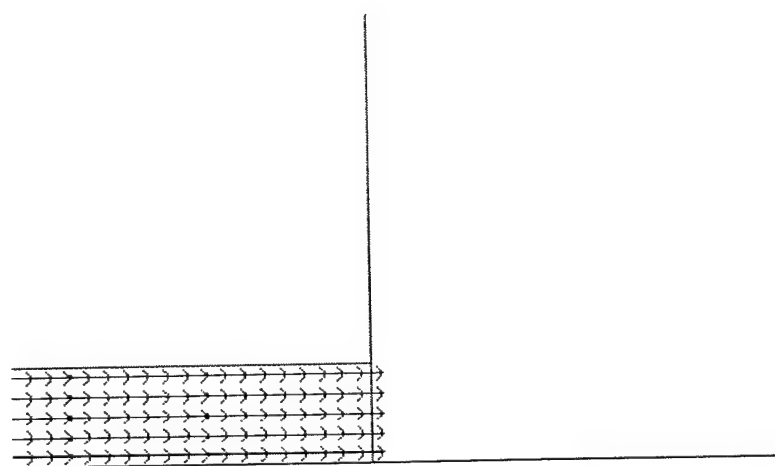


(CM,GM,US)
CYCLE 0
T = 0.000E+00

STEEL INTO STEEL PLANAR



STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.500E-01

Scale

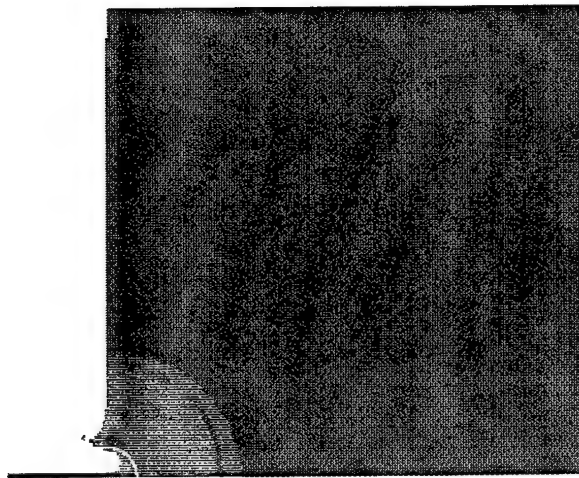
9.100E-01

(CM, GM, US)

CYCLE 0

T = 0.000E+00

STEEL INTO STEEL PLANAR

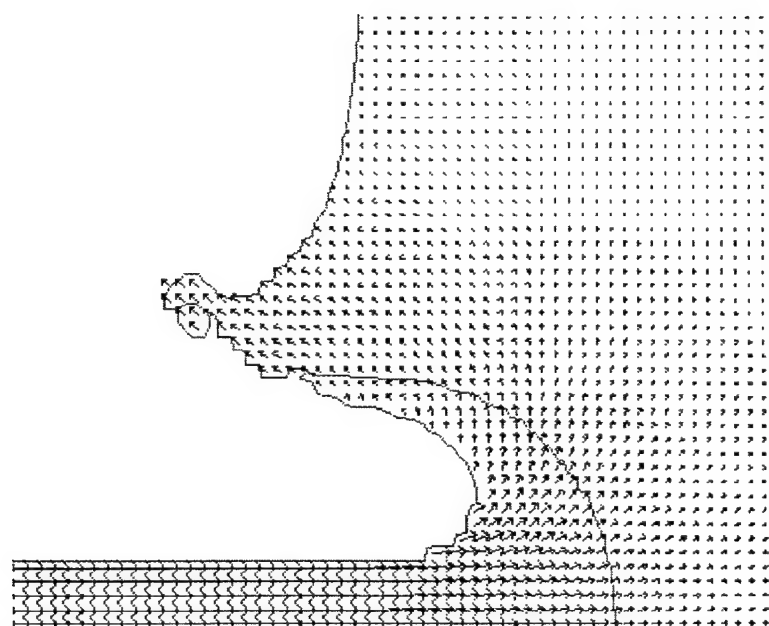


MATERIAL
STATUS

 HYDRO
 ELASTIC
 PLASTIC
 FAILED

(CM,GM,US)
 CYCLE 200
 T = 1.677E+01

STEEL INTO STEEL PLANAR



VELOC
VECTOR

Scal

2.000E

Maximu
Veloci
2.492E

Scal

1.300E

(CM.GM.
CYCLE 2
T = 1.6

STEEL INTO STEEL PLANAR

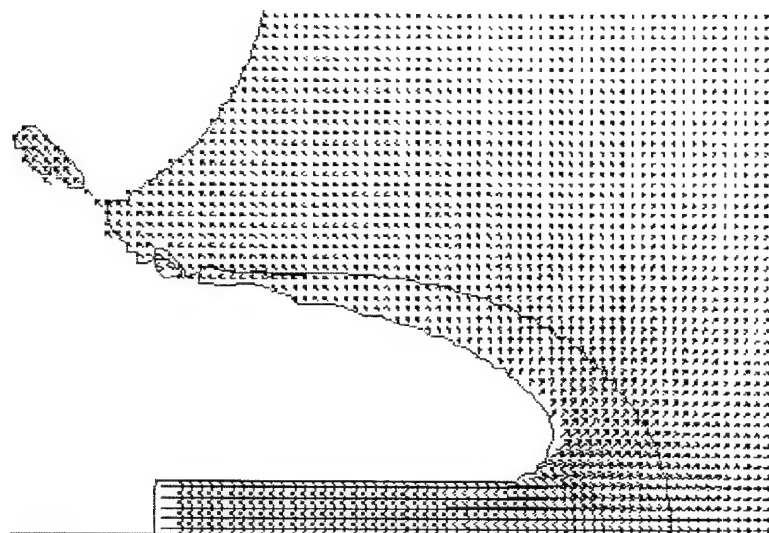


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 400
T = 3.427E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.467E-01

Scale

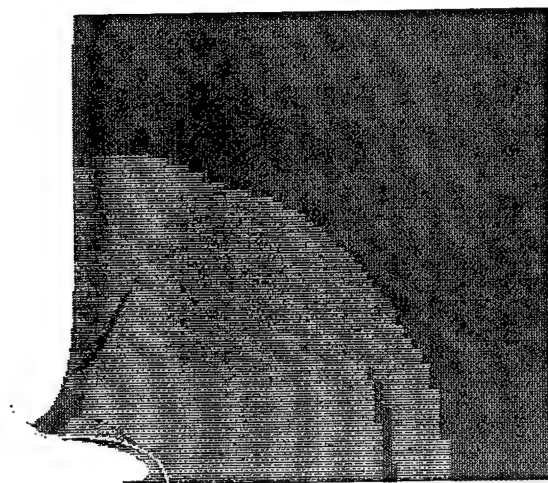
1.700E+00

(cm, gm, us)

CYCLE 400

T = 3.427E+01

STEEL INTO STEEL PLANAR

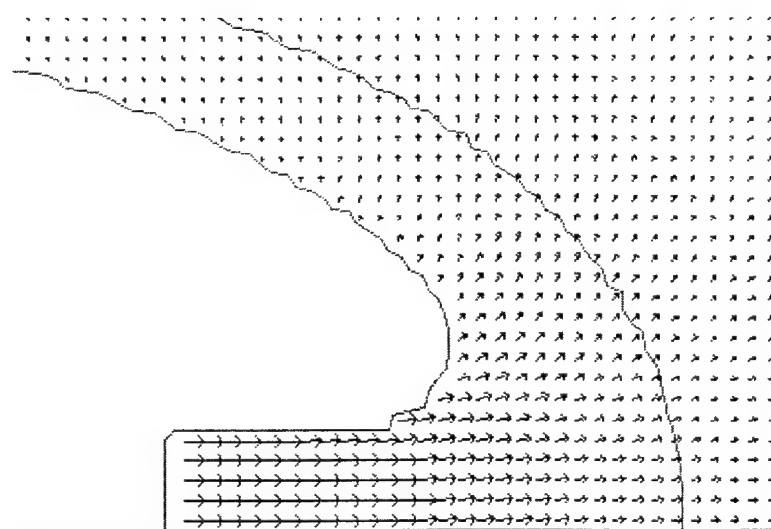


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(cm, gm, us)
CYCLE 600
T = 5.201E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.467E-01

Scale

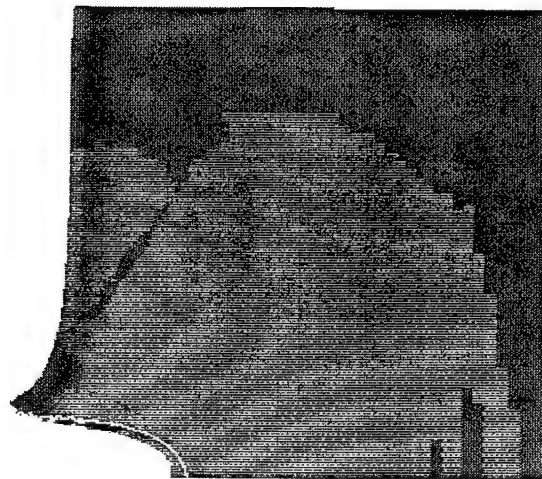
9.100E-01

(cm, gm, us)

CYCLE 600

T = 5.201E+01

STEEL INTO STEEL PLANAR

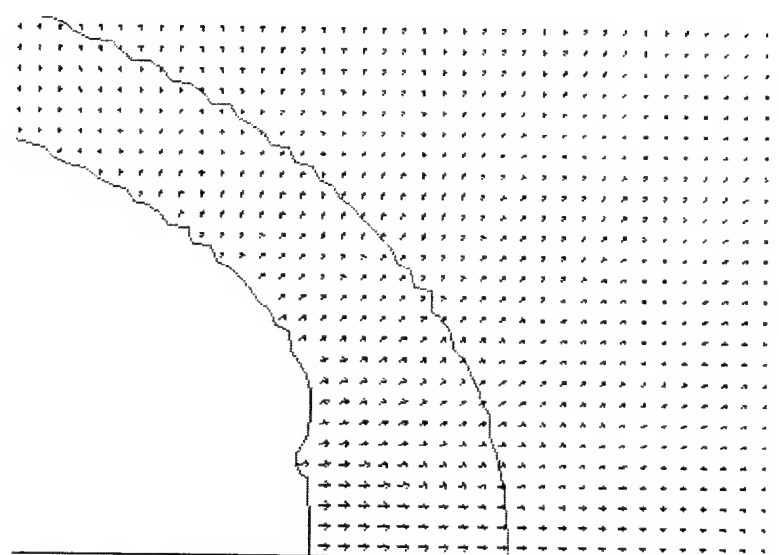


MATERIAL
STATUS

■ HYDRO
 ■ ELASTIC
 ■ PLASTIC
 ■ FAILED

(CM,GM,US)
 CYCLE 800
 T = 7.079E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.467E-01

Scale

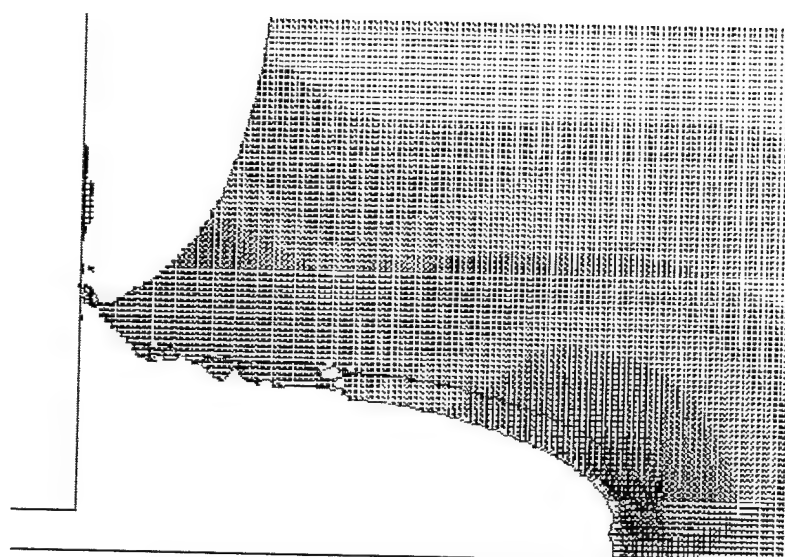
8.800E-01

(cm, gm, us)

CYCLE 800

T = 7.079E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

$2.000E+00$

Maximum
Velocity
 $2.467E-01$

Scale

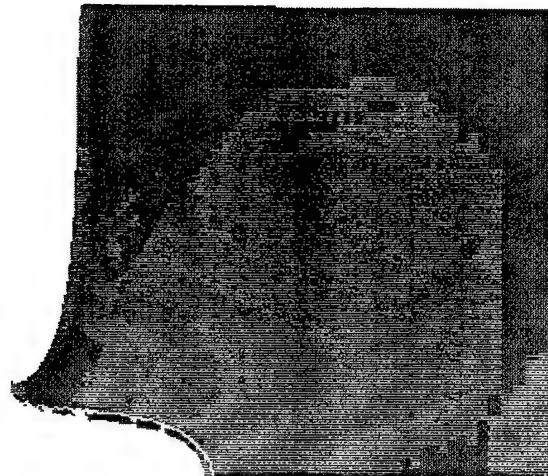
$3.300E+00$

(cm, gm, us)

CYCLE 800

$T = 7.079E+01$

STEEL INTO STEEL PLANAR

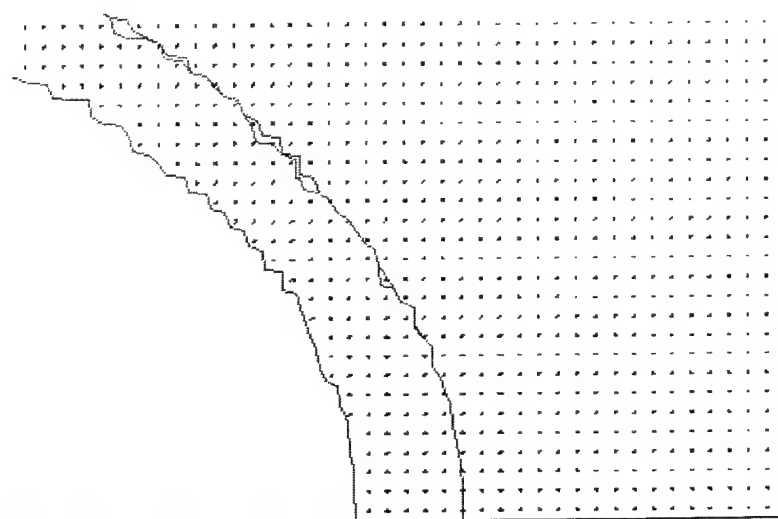


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 1000
T = 9.143E+01

STEEL INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

2.000E+00

Maximum
Velocity
2.467E-01

Scale

9.400E-01

(cm, gm, us)

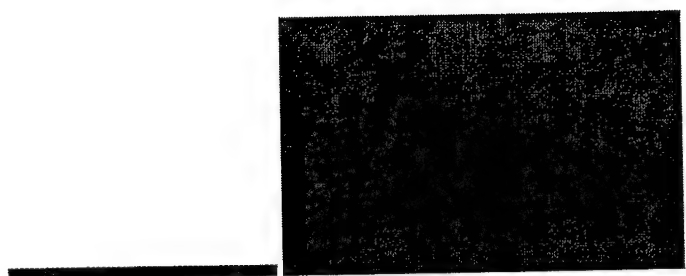
CYCLE 1000

T = 9.143E+

STEEL INTO STEEL PLANAR

Appendix A7

Plots for run No. 7
Tungsten alloy projectile
Axial symmetry
1.5 km/s

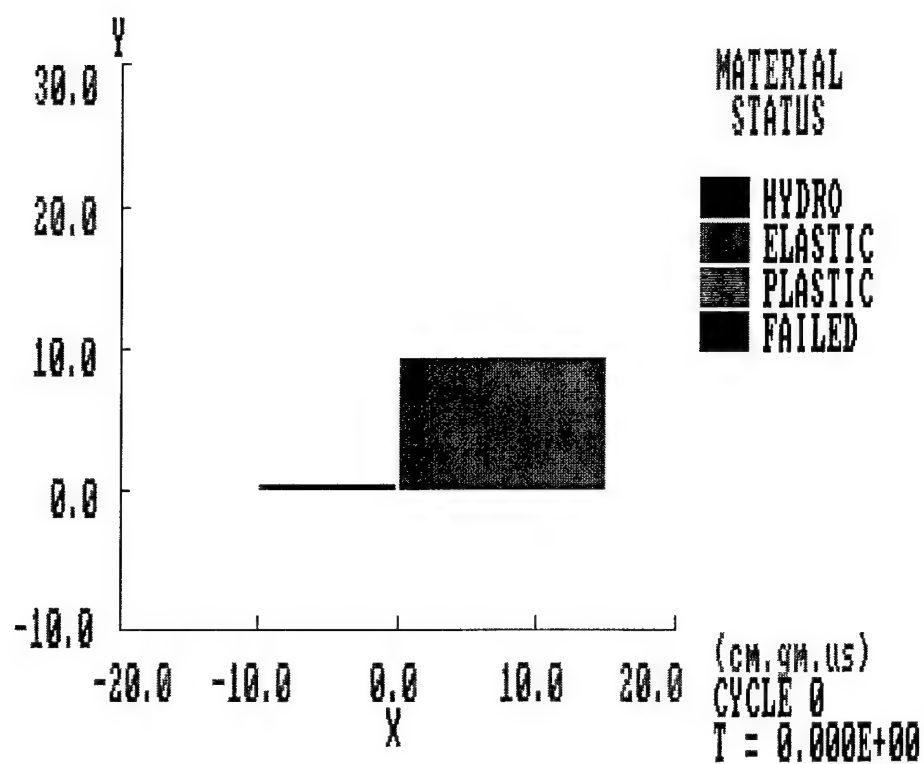


MATERIAL
STATUS

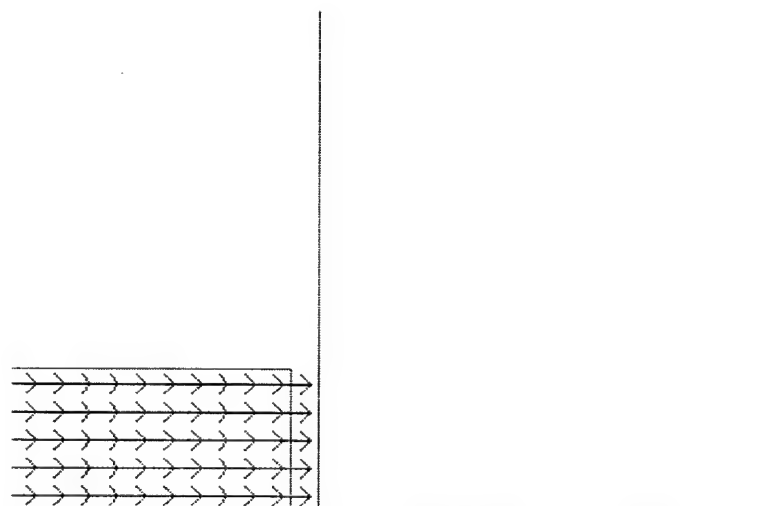
■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM,GM,US)
CYCLE 0
T = 0.000E+00

TUNGSTEN INTO STEEL



TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.500E-01

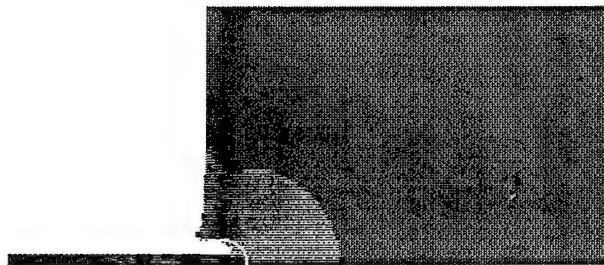
Scale

6.500E-01
(cm, gm, us)

CYCLE 0

T = 0.000E+00

TUNGSTEN INTO STEEL

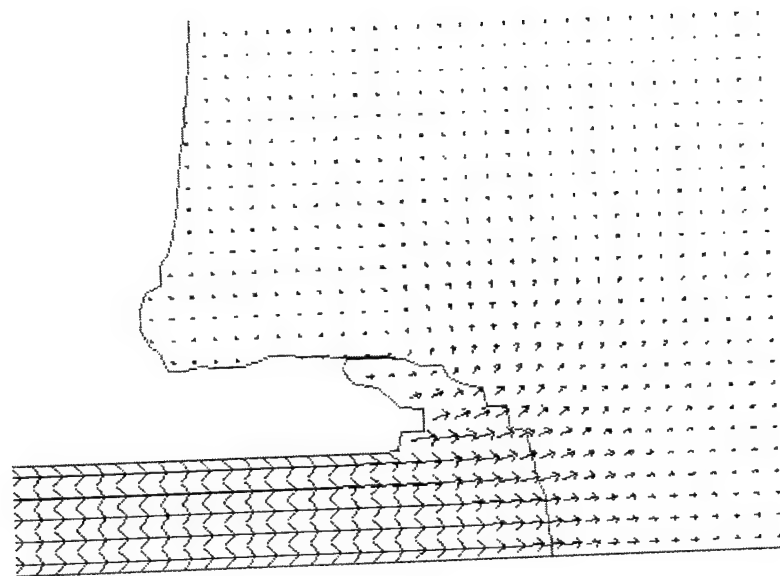


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 200
T = 1.928E+01

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.498E-01

Scale

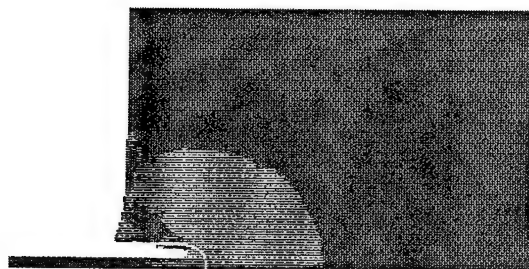
8.400E-01

(CM, GM, US)

CYCLE 200

T = 1.928E+01

TUNGSTEN INTO STEEL

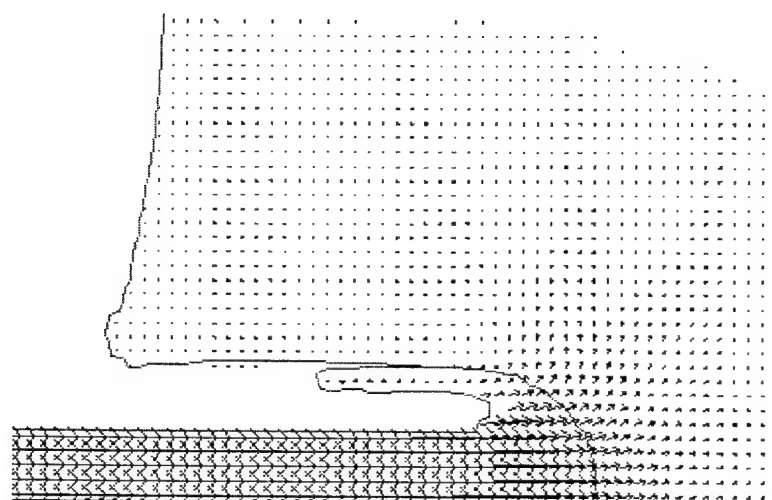


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM, GM, US)
CYCLE 400
T = 3.923E+01

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.460E-01

Scale

1.200E+00

(CM, GM, US)

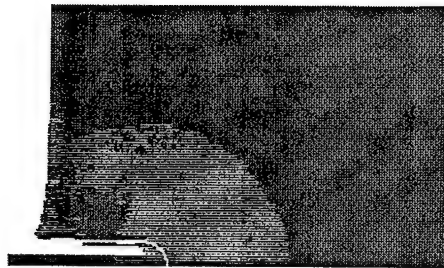
CYCLE 400

T = 3.923E+01

TUNGSTEN INTO STEEL

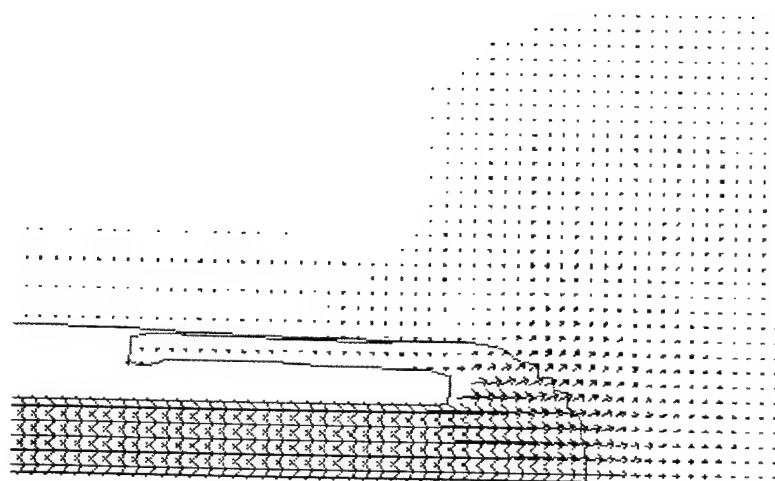
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM,GM,US)
CYCLE 600
T = 5.929E+01

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.460E-01

Scale

1.200E+00

(CM, GM, US)

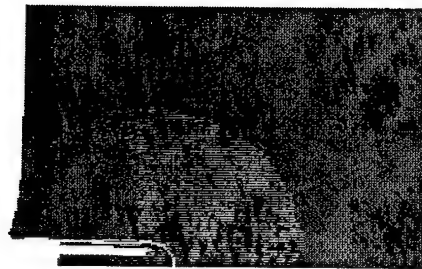
CYCLE 600

T = 5.929E+01

TUNGSTEN INTO STEEL

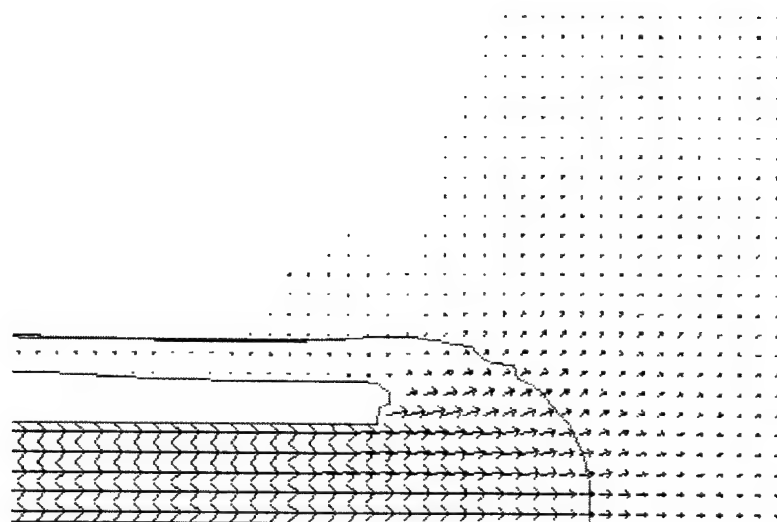
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM,GM,US)
CYCLE 800
T = 7.952E+01

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.460E-01

Scale

9.200E-01

(cm, gm, us)

CYCLE 800

T = 7.952E+01

TUNGSTEN INTO STEEL

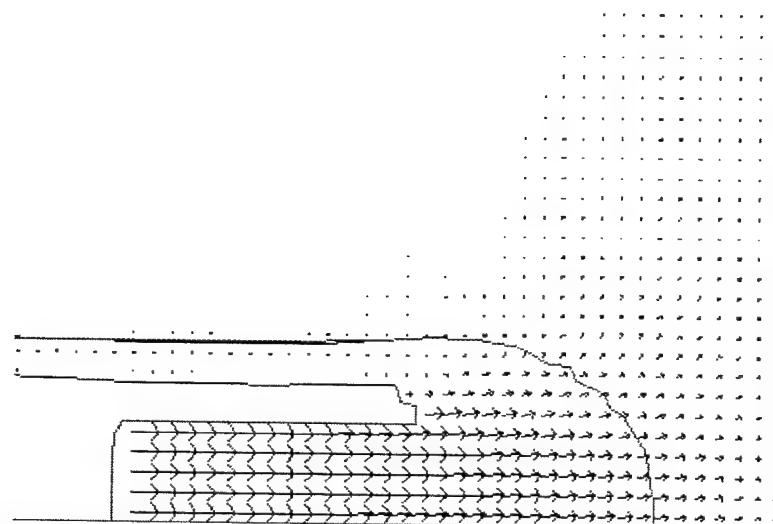


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 1000
T = 1.000E+02

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.460E-01

Scale

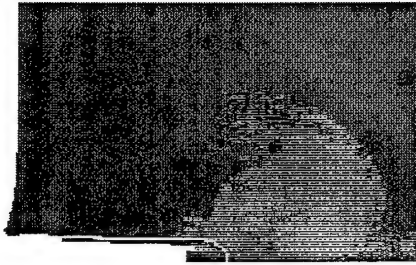
9.200E-01

(cm, gm, us)

CYCLE 1000

T = 1.000E+02

TUNGSTEN INTO STEEL

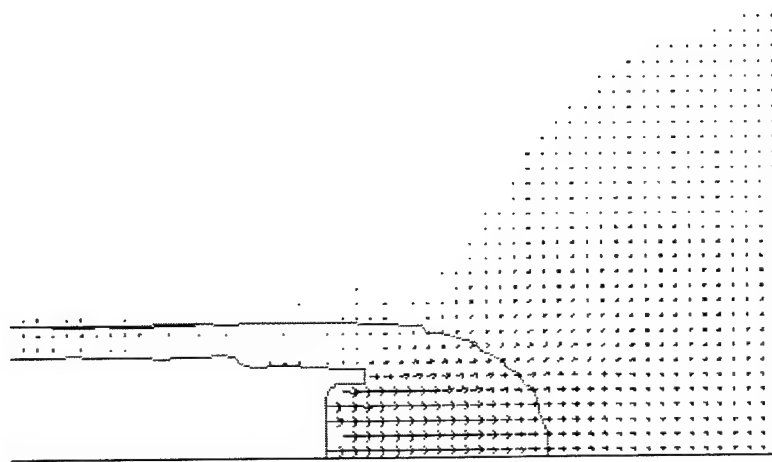


MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM,GM,US)
CYCLE 1200
T = 1.214E+02

TUNGSTEN INTO STEEL



VELOCITY
VECTORS

Scale

→
8.000E-01

Maximum
Velocity
1.460E-01

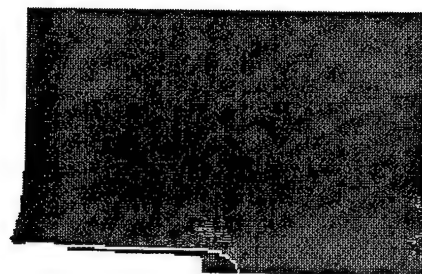
Scale

1.200E+00
(CM, GM, US)
CYCLE 1200
T = 1.214E+02

TUNGSTEN INTO STEEL

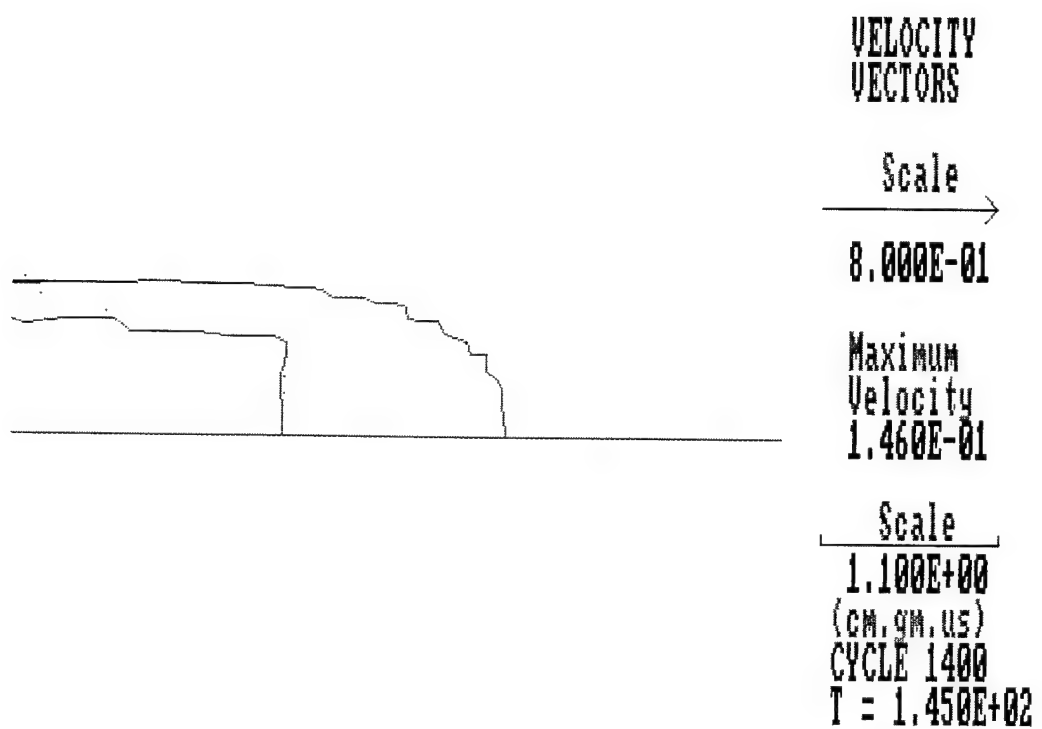
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM, GM, US)
CYCLE 1400
T = 1.450E+02

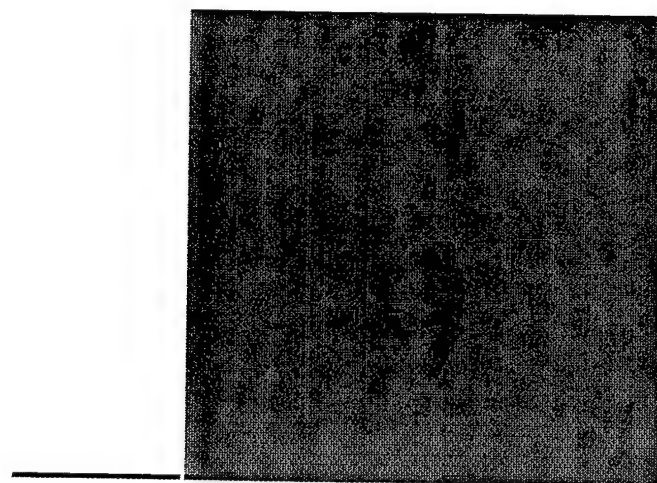
TUNGSTEN INTO STEEL



TUNGSTEN INTO STEEL

Appendix A8

Plots for run No. 8
Tungsten alloy projectile
Planar symmetry
1.5 km/s

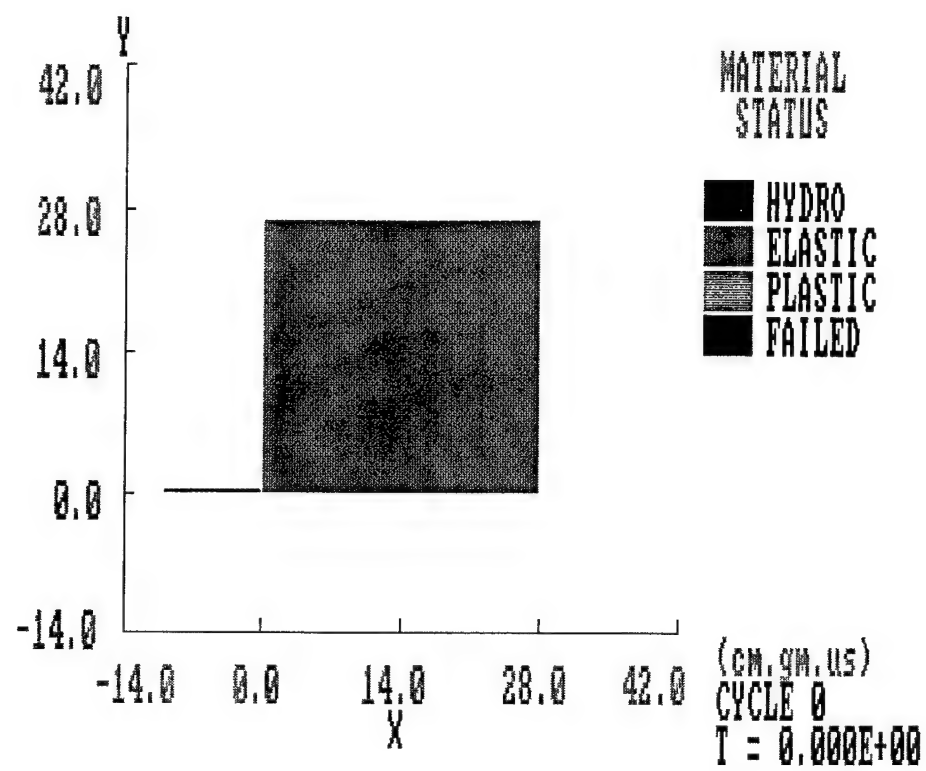


MATERIAL
STATUS

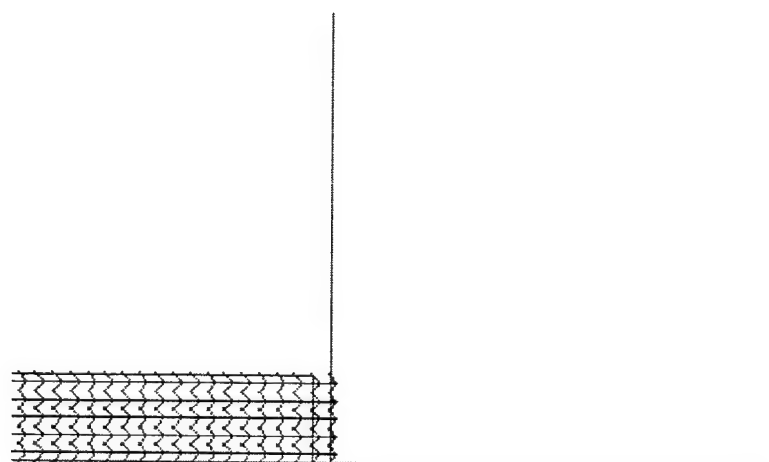
| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 0
T = 0.000E+00

TUNGSTEN INTO STEEL PLANAR



TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.500E-01

Scale

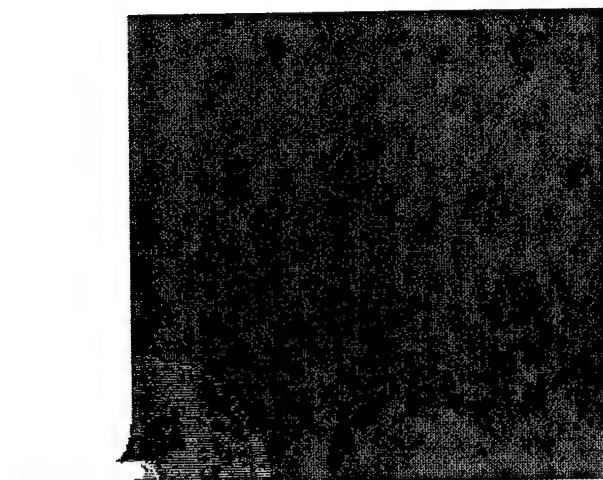
1.000E+00

(cm, gm, us)

CYCLE 0

T = 0.000E+00

TUNGSTEN INTO STEEL PLANAR

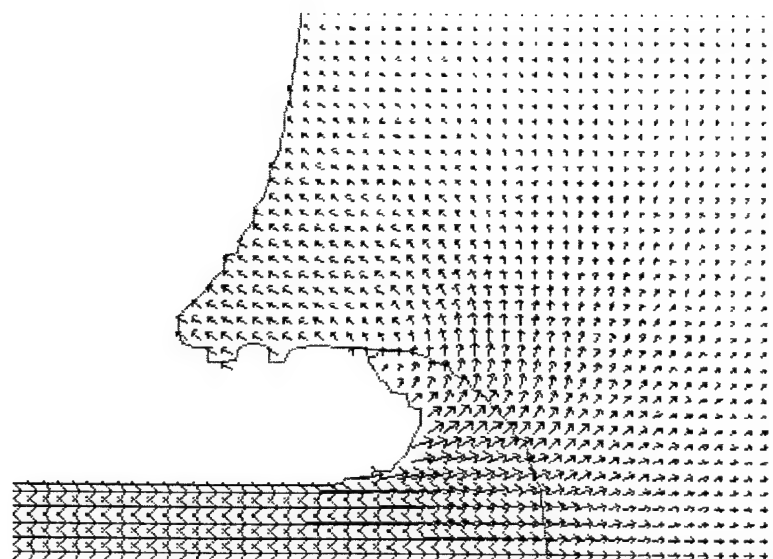


MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED

(CM, GM, US)
CYCLE 200
T = 1.908E+01

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.491E-01

Scale

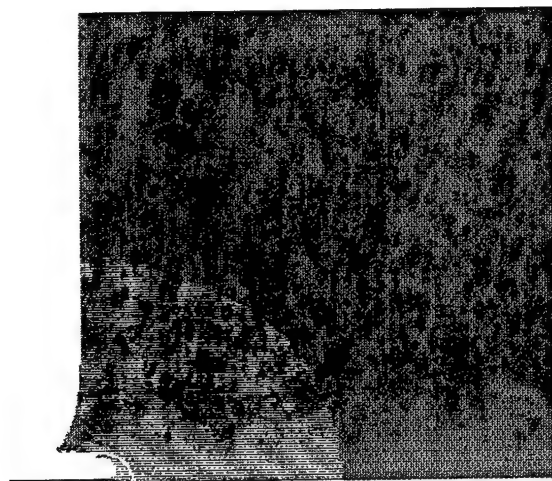
1.100E+00

(cm. gm. us)

CYCLE 200

T = 1.908E+01

TUNGSTEN INTO STEEL PLANAR

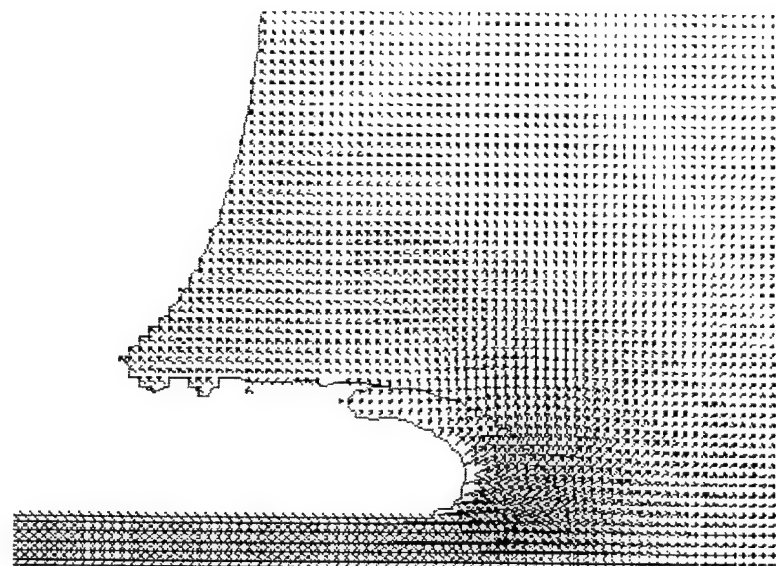


MATERIAL
STATUS

 HYDRO
 ELASTIC
 PLASTIC
 FAILED

(CM.GM.US)
 CYCLE 400
 T = 3.905E+01

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-0

Maximum
Velocity
1.448E-0

Scale

1.800E+0

(CM, GM, US

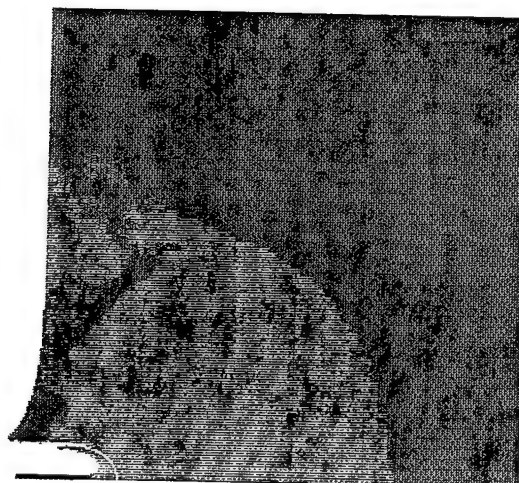
CYCLE 400

T = 3.905

TUNGSTEN INTO STEEL PLANAR

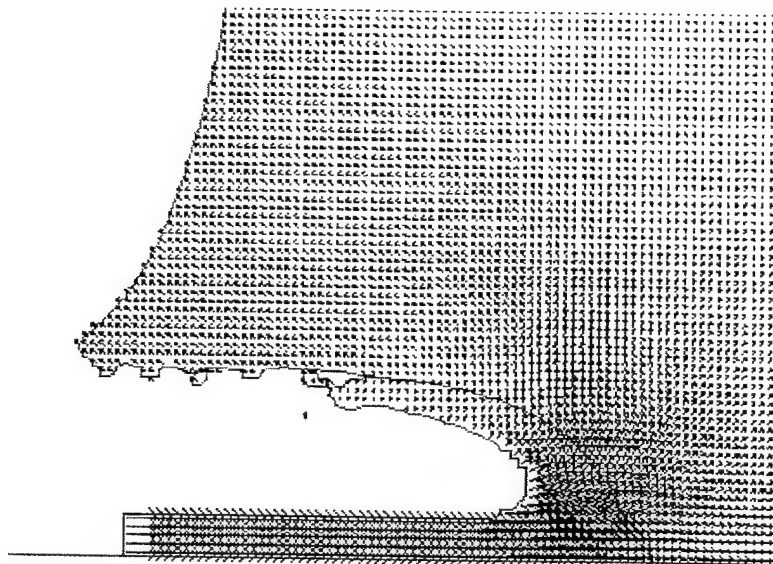
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM, GM, US)
CYCLE 600
T = 5.917E+6

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.448E-01

Scale

2.100E+00

(CM, GM, US)

CYCLE 600

T = 5.917E+01

TUNGSTEN INTO STEEL PLANAR

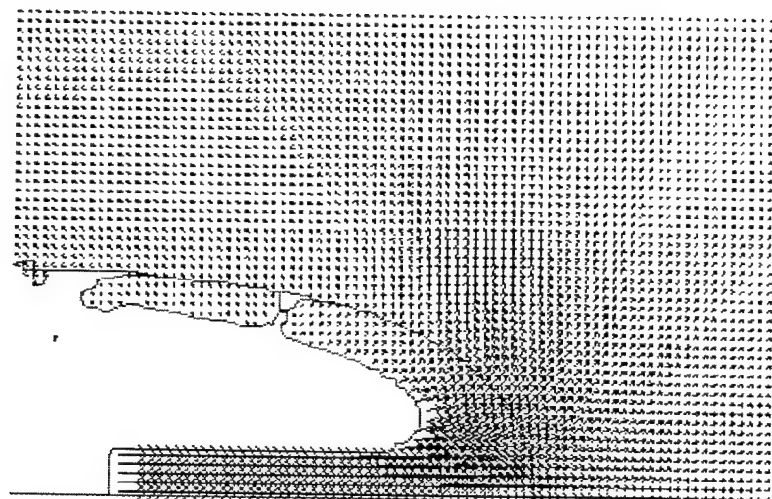


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 800
T = 7.950E+01

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.448E-01

Scale

1.900E+00
(cm. gm. us)
CYCLE 800
T = 7.950E+01

TUNGSTEN INTO STEEL PLANAR

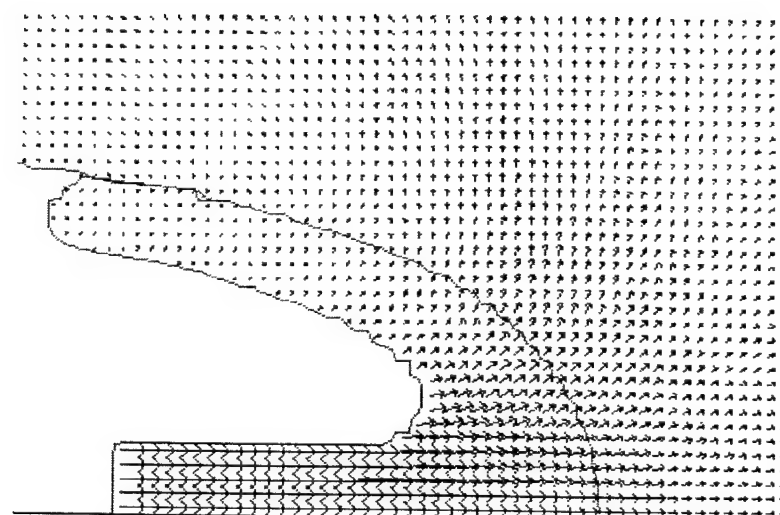
MATERIAL
STATUS

■ HYDRO
■ ELASTIC
■ PLASTIC
■ FAILED



(CM,GM,US)
CYCLE 1000
T = 1.002E+02

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale →

8.000E-01

Maximum
Velocity
1.448E-01

Scale

1.200E+00

(CM. GM. US)

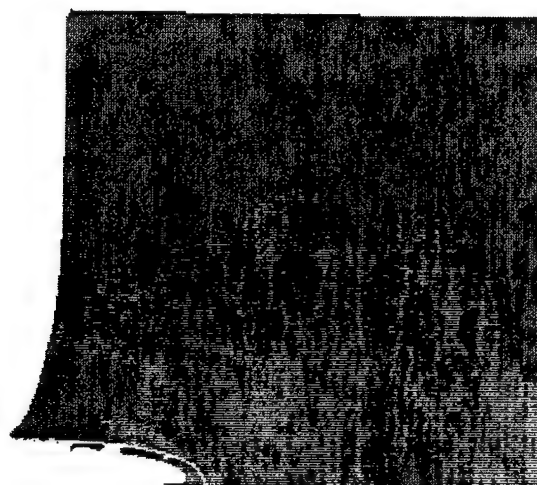
CYCLE 1000

T = 1.002E+02

TUNGSTEN INTO STEEL PLANAR

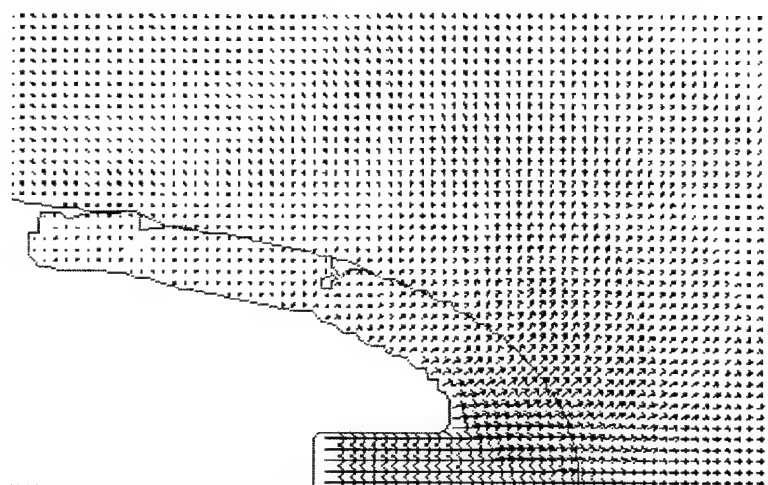
MATERIAL
STATUS

| | |
|---|--------|
| ■ | HYDRO |
| ■ | ELASTI |
| ■ | PLASTI |
| ■ | FAILEI |



(CM, GM, US
CYCLE 120
T = 1.214

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale →

8.000E-01

Maximum
Velocity
1.448E-01

Scale

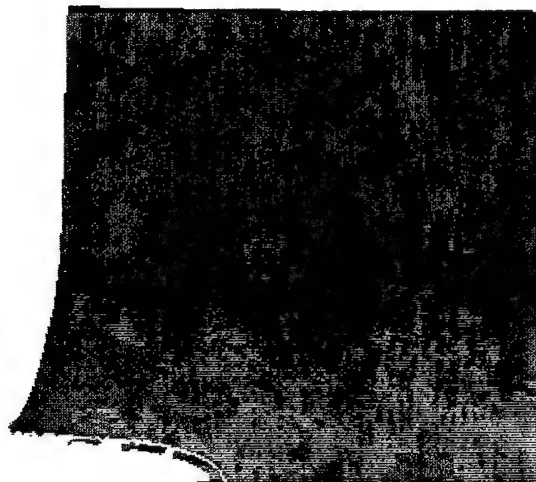
1.600E+00

(cm, gm, us)

CYCLE 1200

T = 1.214E+02

TUNGSTEN INTO STEEL PLANAR

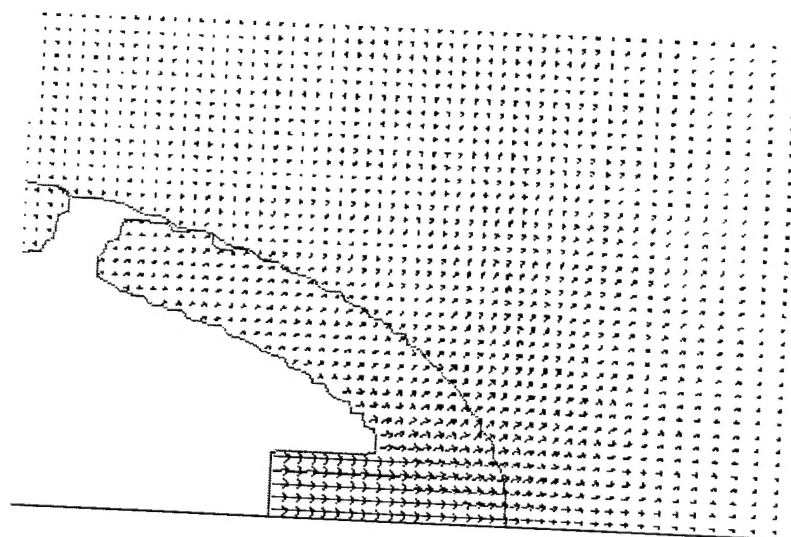


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM.GM.US)
CYCLE 1400
T = 1.436E+02

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

$8.000E-01$

Maximum
Velocity
 $1.448E-01$

Scale

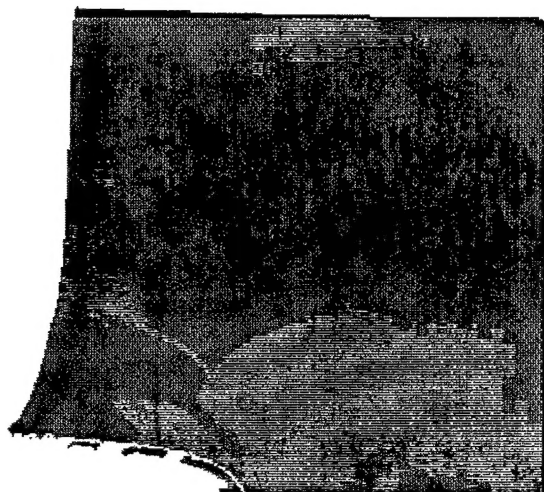
$1.300E+00$

(cm.gm.us)

CYCLE 1400

$T = 1.436E+02$

TUNGSTEN INTO STEEL PLANAR

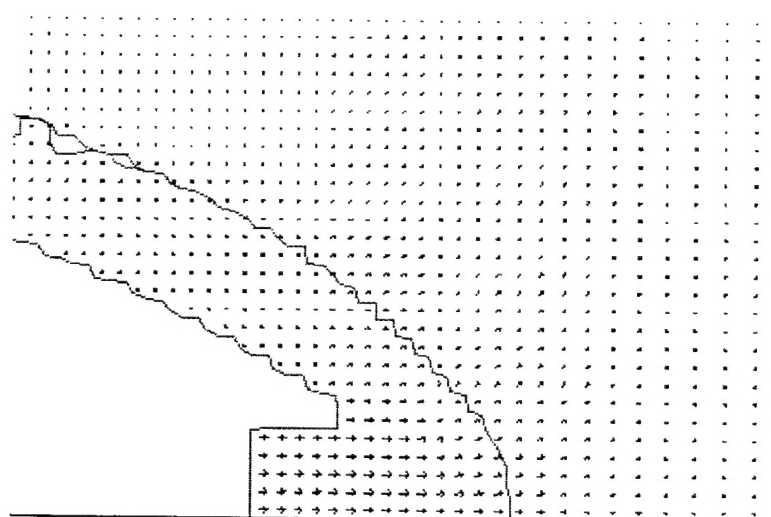


MATERIAL
STATUS

| | |
|---|---------|
| ■ | HYDRO |
| ■ | ELASTIC |
| ■ | PLASTIC |
| ■ | FAILED |

(CM,GM,US)
CYCLE 1600
T = 1.665E+02

TUNGSTEN INTO STEEL PLANAR



VELOCITY
VECTORS

Scale

8.000E-01

Maximum
Velocity
1.448E-01

Scale

1.000E+00
(cm.gm.us)
CYCLE 1600
T = 1.665E+02

TUNGSTEN INTO STEEL PLANAR

Appendix B Distribution List

Administrator
Defense Technical Information Center
Attn: DTIC-DDA
8725 John J. Kingman Road, Ste 0944
Ft. Belvoir, VA 22060-6218

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2800 Powder Mill Road
Adelphi, MD 20783-1145

Director
US Army Research Lab
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2800 Powder Mill Road
Adelphi, MD 20783-1145

Director
US Army Research Lab
ATTN: AMSRL OP SD TP
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Adelphi, MD 20783-1145

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Army Research Laboratory
AMSRL-CI-LP
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